

# ESSAYS ON SUSTAINABLE OPERATIONS

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# ESSAYS ON SUSTAINABLE OPERATIONS

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## SUMMARY

With the increased attention of different stakeholders on the environmental performance of businesses, several firms are increasingly focusing on product recovery and reuse activities which are not only profitable but may also help to reduce the environmental impact of their operations. This dissertation focuses on managerial challenges associated with such value-added recovery and reuse activities. The first essay (Chapter 2) examines how a firm should bring a product to market, in particular, whether to lease or sell products. Motivated by claims that leasing can be an environmentally superior to selling, we analytically investigate if either leasing or selling can be both more profitable for a monopolist and have a lower total environmental impact. The second essay (Chapter 3) first experimentally examines the effect of remanufactured products on the perceived value of new products. This effect is then incorporated to analytically investigate an OEM's strategy in the presence of competition from third-party remanufacturers. In the third essay (Chapter 4), motivated by a major IT company, we investigate the optimal product recovery and remanufacturing strategy for a firm that can offer trade-in rebates to achieve price discrimination. We also consider the effect of potential entry of third-party remanufacturers on the firm's recovery and remanufacturing strategy.

# CHAPTER I

## INTRODUCTION

The growth in industrial production and increased consumption by a growing population are increasing the strain on the environment. The resulting regulatory and consumer attention on the environmental performance of businesses has led to an increase in managerial focus on sustainability. This has led many firms to adopt or explore the benefits of product recovery and reuse activities which could potentially reduce the environmental impact of their businesses. A critical challenge for managers in operationalizing these strategies is how to ensure that they not only reduce the environmental impact of their operations but also do not have a detrimental effect on their profitability. This dissertation focuses on managerial challenges associated with such value-added recovery activities.

The first essay, presented in Chapter 2, investigates whether leasing can be greener than a selling strategy. Based on the proposition that leasing is environmentally superior to selling, some firms have adopted a leasing strategy and others promote their existing leasing programs as environmentally superior in order to “green” their image. The argument is that as a leasing firm retains ownership of the off-lease units, it has an incentive to remarket the products, resulting in a lower production and disposal volume. However, some argue that leasing might be environmentally inferior due to the direct control the firm has over the off-lease products, which may prompt their premature disposal to avoid cannibalizing the demand for new products. Motivated by these issues, we adopt a life-cycle environmental impact perspective and analytically investigate if either leasing or selling can be both more profitable for a monopolist and have a lower total environmental impact. We identify conditions

where each of these outcomes can occur, depending on the magnitude of the disposal cost, the differential in disposal costs faced by the firm and consumers, and the environmental impact profile of the product. These results provide insights for firms who want to promote their strategy as the “greener” choice.

In the second essay, presented in Chapter 3, we experimentally investigate the effect of remanufactured products on the perceived value of new products. We find that the perceived value of an OEM’s new product depends on who sells the remanufactured product: in our experiment, the perceived value of new products decreases when the OEM sells the remanufactured product, but it increases when the remanufactured product is sold by a third-party remanufacturer. We incorporate this effect to analytically investigate an OEM’s strategy in the presence of competition from third-party remanufacturers. Existing literature has argued that because the presence of third-party competition is detrimental for the OEM, it should pursue remanufacturing or collection of used products to preempt third-party remanufacturers. By incorporating the effect of remanufacturing on the perceived value of new products, our research shows that an OEM may not always benefit from preempting third-party remanufacturers. Instead, an OEM may find it more profitable to allow third-party competitors to remanufacture its products.

The third essay, presented in Chapter 4, is motivated by the practices at a major IT company. In this essay, we study the impact of trade-in rebates to practice price discrimination, when the recovered products can be remanufactured and remarketed to consumers. Although the magnitude of the customized rebate given by the firm is supposedly based on the condition of the used product, we observed that there is very low correlation between the rebate given and the physical condition of the returned products. We find that even if disposal of returns is costly, it is optimal for the firm to offer a trade-in program, due to the benefits of price discrimination. We also show that the firm is less likely to remanufacture when it has the opportunity to practice

price discrimination. This may potentially explain why some firms recover products through trade-ins but not choose to remanufacture in practice. Since the trend is towards increasing competition from third-party remanufacturers and increasing disposal costs, we consider the firm's recovery and remanufacturing strategy in the presence of threat of entry by a third-party competitor. We find that a firm may choose to remanufacture to deter entry of such competitors, despite cannibalization of new products and a reduced ability to practice price discrimination.

## CHAPTER II

### IS LEASING GREENER THAN SELLING?

#### *2.1 Introduction*

Leasing is a strategy prevalently used by durable goods manufacturers. Academic research in economics and marketing has identified conditions for the profitability of this strategy (Coase, 1972; Bulow, 1982; Hendel and Lizzeri, 1999b; Desai and Purohit, 1998, 1999). Recently, there have been claims that leasing can be a greener strategy, leading to a lower environmental burden than selling (Hawken et al., 1999; Fishbein et al., 2000; Mont, 2002). The argument is the following: Since the firm maintains ownership of the product under an operating lease, it has an incentive to efficiently remarket the used product at the end of the lease duration<sup>1</sup>. Remarketing the product as opposed to disposing of it<sup>2</sup> decreases the demand for new products, reducing the environmental impact of manufacturing and disposal.

Some firms seeking to “green” their image in response to growing consumer awareness of environmental issues have embraced the “Leasing is Green” message. For example, Interface Inc., a carpet manufacturer, introduced the Evergreen Lease<sup>TM</sup> with the express purpose of reducing the environmental impact of its products and described it as a “new workable business model for sustainable development” (Olivia and Quinn, 2003). Interface chairman and founder Ray Anderson states “Leasing carpet rather than selling it, and being responsible for it cradle to cradle, is the future” (Anderson, 1998). Others promote their leasing programs as being environmentally friendly. According to IBM, “..leasing makes more and more sense for many clients.

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<sup>1</sup>In this paper, the term “remarketing” refers to putting the used product on the market.

<sup>2</sup>In this study, the term “disposal” refers to taking the used product off the market via recycling, incineration or landfilling.

Clients enjoy the benefits of technology without having to dispose of equipment at the end of its useful life...Combined with the simplicity of returning equipment to IBM at end of lease, IBM essentially uses Best Practice in Asset Management to keep equipment out of the waste stream” (IBM, 2007). Indeed, IBM’s Global Asset Recovery Services, which is part of IBM Global Financing, remarkets 85% of off-lease machines it receives worldwide (Johnson, 2007). HP’s environmental sustainability report states “Product reuse programs extend the useful life of equipment, especially at the end of leasing agreements when consumers return products ranging from PCs to data center equipment” (Hewlett-Packard , 2009). Xerox named its line of refurbished off-lease products the “Green Line” to emphasize the environmental benefits of their approach (Charter and Polonsky, 1999). Several environmental policy-making groups such as the U.S. Environmental Protection Agency, the state of Minnesota and the New York City Government (U.S. EPA, 2008a; Minnesota Pollution Control Agency , 2006; New York City Government, 2007) also recommend leasing as an environmentally superior strategy.

In contrast, some argue that the environmental superiority of leasing is far from clear (Ruth, 1998), and some even argue it is a “fallacy” (Lawn, 2001). The reason is the direct control that the firm exerts on the off-lease units. To avoid cannibalizing the demand for the firm’s new products, a leasing firm may remove the returned used products from the market. For example, the majority of Pitney Bowes’ off-lease products are not remarketed (Fishbein et al., 2000), and a computer network equipment manufacturer is known to have prematurely disposed of fully functional products worth more than \$700 million (Guide and Van Wassenhove, 2009). Such premature disposal may result in a higher manufacturing and disposal volume than selling, causing leasing to underperform from a total life-cycle environmental impact perspective. The life cycle of a product consists – at its most basic – of the production, use and disposal phases. We define the total life-cycle environmental impact of a strategy

as the volume of products in each phase multiplied with the per unit environmental impact in that phase, summed over all life-cycle phases. Under leasing, the product volumes in each life-cycle phase are determined by the production, remarketing and disposal volumes. Under selling, they are determined by the production volume and the size of the secondary market.

In this study, we rigorously analyze the impact of key drivers determining whether leasing can be greener than selling. Our goal is to establish when a firm can justifiably claim leasing to be environmentally superior to selling, which is valuable in an environment where consumers are sensitive to “greenwashing” and the internet makes information about offenders easy to publicize and access (e.g. through sites such as [www.greenwashingindex.com](http://www.greenwashingindex.com)). We identify conditions under which leasing dominates by being environmentally superior *and* profitable, but also those conditions under which selling is better along both dimensions, providing new support for a selling firm’s environmental positioning.

In comparing the two strategies, we add a new feature to the traditional leasing model by jointly incorporating a disposal cost and allowing for the disposal of off-lease products by the firm. Disposal costs have recently become an important consideration due to increases in landfilling fees and a growing patchwork of legislation governing post-use products (Luther 2008), as well as firms choosing more costly but environmentally preferred methods of disposal to avoid a negative environmental image. The product disposal cost plays a critical role in the volume of products in each life-cycle phase: Under leasing, the firm maintains ownership of the off-lease units, so the remarketing and disposal decisions depend on the disposal cost faced by the firm. Under selling, it is the consumer who disposes of the product. The firm typically avoids direct disposal costs, but has to implicitly bear the consumer’s disposal cost (if any) and the loss of control over the secondary market. Thus, the presence of disposal costs affects the profitability and the environmental impact of



leasing and selling differently and is important to capture in any model comparing the two. Since there is often a differential in disposal costs faced by the firm and consumers, we allow for asymmetry in the disposal costs in our analysis.

Our work builds on and contributes to the previous literature on durable goods, closed-loop supply chains and industrial ecology. In the durable goods literature, several issues associated with the lease versus sell decision faced by a firm have been studied (for an excellent overview, see Waldman, 2003). Some of these issues include pricing power (Coase, 1972; Stokey, 1981; Bulow, 1982; Bagnoli et al., 1989; Karp, 1996; Kühn, 1998; Hahn, 2006), the role of secondary markets and market segmentation (Waldman, 1997; Hendel and Lizzeri, 1999b; Desai and Purohit, 1998; Huang et al., 2001), competition (Desai and Purohit, 1999; Huang and Kuzyutin, 2002) and channel structure (Purohit, 1995, 1997; Desai et al., 2004; Bhaskaran and Gilbert, 2009). The main focus of this stream of literature is to analyze the relative profitability of leasing and selling, or to explain the coexistence of these strategies.

We make two distinct contributions to this literature. First, our work brings the environmental impact dimension to the comparison of leasing and selling. Second, we enrich the comparison of the two strategies by incorporating disposal costs faced by both the firm and the consumers and endogenizing premature disposal in this setting. We compare both the profitability and the environmental impact of leasing versus selling and find that all four combinations are possible (selling is more profitable and environmentally superior, leasing is more profitable but selling is environmentally superior, etc.), depending on the inherent durability of the product, the structure of the disposal costs, and which phases of its life cycle contribute the most to the product's environmental impact. Several papers have identified settings where selling may be more profitable: the presence of competition or the threat of entry (Bucovetsky and Chilton, 1986; Desai and Purohit, 1999), lower durability under selling (Desai and

Purohit, 1998), the presence of production lead-time and demand uncertainty (Desai et al., 2004), and the presence of complementary goods (Bhaskaran and Gilbert, 2005). We identify another setting by showing that selling may be more profitable when a firm faces higher disposal cost than consumers.

In the closed-loop supply chain literature, a number of papers focus on the joint pricing of new and remarketed products under the selling strategy in a variety of competitive and regulatory environments (Debo et al., 2005; Heese et al., 2005; Ferrer and Swaminathan, 2006; Ferguson and Toktay, 2006; Jin et al., 2007; Atasu et al., 2008b; Esenduran et al., 2008). In these papers, however, there is an assumption that the product has a useful life of only one period and has to be remanufactured or refurbished before it can be used again. This characterization blurs the distinction between leasing and selling, as no consumer-to-consumer trading occurs and the firm has full control of used products even under selling. We complement this literature by considering a firm’s disposal and remarketing decisions for a durable product having a useful life of two periods, which makes the distinction between the two strategies particularly salient. Debo et al. (2005) argue that adding a disposal cost would simply increase the effective cost of production. We formalize this argument, and show that a disposal cost differential leads to cases where selling a durable good can be more profitable than leasing it.

In the industrial ecology literature, the environmental impact of products is evaluated by using conventional life-cycle analysis that focuses on the impact of one unit throughout its life cycle (U.S. EPA, 2008c). Firms such as Nokia, Canon and Apple use LCA results to aid decision-making and provide this information to consumers (McLaren and Piukkula, 2004; Canon, 2009; Apple, 2009a). LCAs may also form the basis for policy recommendations (European Environmental Agency, 1998; Tukker et al., 2005; U.S. EPA, 2008c). However, as pointed out by Thomas (2008), focusing

on per-unit impact ignores market effects such as demand and use duration that determine total environmental impact. In this study, we formalize the market effects by including sale, disposal and use volumes in the calculation of the total life-cycle environmental impact of the firm's chosen strategy. As we assume that the product's per unit environmental impact is the same whether it is sold or leased, all the conclusions we draw about relative environmental impact are driven by the market effects.

The rest of the essay is organized as follows: In §2.2, we discuss our assumptions and develop discrete-time, infinite horizon, dynamic sequential games for the leasing and selling strategies. In §2.3, we solve for the optimal strategies of a monopolist. In §2.4, we use the optimal decisions found in the previous section to compare the relative profitability and total environmental impact of the two strategies. Finally, in §2.5, we conclude by discussing the managerial insights derived from our analysis. All proofs are included in the Appendix.

## ***2.2 The Model***

In this section, we outline our assumptions regarding the product, firm, consumer and market characteristics, and end with the specification of a discrete-time dynamic sequential game over an infinite time horizon. In the remainder of the essay, vectors are arranged in rows and primes represent transposes.  $\mathbf{1}$  denotes a vector of ones. Superscripts are used to label time and subscripts are used to label other information.  $f$  and  $c$  denote firm and consumer specific parameters, respectively.

**Firm and Product Characteristics.** We study a profit-maximizing monopolist that produces a single durable product. The firm has a constant returns to scale production technology with the marginal cost of producing a new product denoted by  $c$ . The product depreciates with use and has finite durability. To capture the intertemporal substitution effect due to product durability while maintaining tractability,

we assume the product lasts for two periods. This assumption has been used extensively in the durable goods literature (Bulow, 1982; Hendel and Lizzeri, 1999a; Desai and Purohit, 1998, 1999; Hendel and Lizzeri, 1999b; Huang et al., 2001; Bhaskaran and Gilbert, 2005) and does not restrict the generality of the insights obtained. We refer to a product in its first period of useful life as *new* and in the second period as *used*. Subscripts  $n$  and  $u$  denote new and used products respectively. Products that have been used for two periods are called *end-of-life* products, and can only be disposed of (via recycling, incineration or landfilling).

The firm uses either a pure leasing strategy or a pure selling strategy. If the firm chooses the leasing strategy, it offers one-period operating leases, where products are returned to the firm after the lease period. The firm may either lease or dispose of the used product, and disposes of end-of-life products; the implications of the firm selling the used products instead of leasing them are discussed in §2.4. If the firm chooses the selling strategy, it sells new products only; used products are traded between consumers on the secondary market at the market clearing price. Under selling, it is the consumers who dispose of end-of-life products.

If the firm remarkets or the consumer sells the used product, they incur remarketing or transaction costs,  $\beta_f \geq 0$  and  $\beta_c \geq 0$ , respectively. Similarly, if the firm or the consumer disposes of products, they incur a unit cost,  $s_f$  and  $s_c$ , respectively. We allow  $s_f$  and  $s_c$  to either be positive or negative, reflecting costly or profitable disposal, but for brevity use the term “disposal cost” to refer to both cases.

There are several factors that determine how costly or profitable disposal is. The product type is a primary factor, in particular, whether the product is mainly composed of metal, plastic, glass, etc. and whether it has toxic material content (Van Wassenhove et al., 2004). For example, cars can typically be sold to scrap yards, but electronic waste is typically costly to dispose of. State and federal legislation is

another factor. For example, some states ban landfilling and/or incineration of certain materials, requiring either costly processing or transportation over long distances (Luther, 2008). In the absence of regulation, a firm may nevertheless undertake costly recycling to avoid a negative environmental perception. For the consumer, disposal can be either costly (paying a fee to remove and dispose a bulky product such as a refrigerator), profitable (selling a product with high value to a recycler) or even free (throwing it in the trash). The disposal cost for a given product need not be the same for the firm and consumers, and can be either higher or lower. For example, federal law on hazardous substances (U.S. EPA, 2008b) does not restrict households from throwing their electronic waste in the trash ( $s_c < s_f$ ). On the other hand, even if recycling is profitable, recyclers may only purchase from firms that generate large volumes, and the recycling opportunity may not be available for consumers ( $s_f < 0 \leq s_c$ ).

**Consumer Characteristics.** The consumer population remains constant over time and is normalized to size 1. Consumers are heterogeneous in the utility they derive from consumption, and are characterized by their type  $\theta$ . We assume that  $\theta$  is uniformly distributed on  $[0, 1]$ . Consumer  $\theta$  is characterized by the utility vector  $u(\theta) \doteq (u_n(\theta), u_u(\theta), 0)$ , where  $u_n(\theta)$  and  $u_u(\theta)$  are the utilities derived from one period use of the new and the used product, respectively, and zero is the utility derived from remaining inactive.  $u(\theta)$  is time independent and exogenous. Ceteris paribus, every consumer (weakly) prefers a new product to a used product, and a used product to remaining inactive;  $u_n(\theta) \geq u_u(\theta) \geq 0$  for all  $\theta \in [0, 1]$ . It is reasonable to expect that the consumer's utility for a product is finite, i.e.,  $\exists M > 0$  such that  $u_n(1) < M$ . As in Desai and Purohit (1998), we assume that the drop in utility between using a new and a used product is higher for consumers with a higher type ( $d(u_n(\theta) - u_u(\theta))/d\theta > 0$ ).

The following assumption satisfying the conditions above is often made in the literature (Desai and Purohit, 1998; Desai et al., 2004; Desai and Purohit, 1999; Desai et al., 2007):

ASSUMPTION A1.  $u_n(\theta) = \theta$  &  $u_u(\theta) = \delta\theta$ , where  $\delta \in (0, 1]$  is interpreted as product durability.

Unless otherwise specified, our results are proven for the generic utility function. Assumption A1 is used to obtain closed-form solutions and enable a detailed comparison of leasing and selling. Under Assumption A1, the condition  $c + \max(s_c, s_f) + \beta_c < 1$  eliminates uninteresting cases where the business is not profitable for the firm.

**Specification of the Game.** We develop a dynamic game where the firm and consumers move sequentially in each period. In every period, the firm first makes her decisions, followed by the consumers. Under a leasing strategy, the firm chooses the quantity of new and used products to lease. The remaining used products and all end-of-life products are disposed. Under the selling strategy, the firm only decides the quantity of new products to sell. Observing these decisions, the consumers play the game strategically against the manufacturer. All players in the game are rational and maximize their net present values with a common discount factor of  $0 < \rho \leq 1$ . All information regarding the cost structures and preferences are common knowledge.

We model the problem as a discrete-time infinite-horizon problem, where periods are indexed by  $t \geq 0$ . The reasons for this are two-fold: First, at the start of the game,  $t = 0$ , there are no existing used products, so there is an initial transient time where the supply of used products builds up. Second, using a finite horizon requires specifying artificial terminal conditions. Consequently, using a finite time horizon would skew the life-cycle based comparison of the two strategies. Thus, we use an infinite time horizon and focus on the steady-state firm and consumer strategies. Our insights are still valid for problems with finite, but sufficiently long horizons.

## 2.3 Analysis

In this section, we analyze the leasing and selling strategies. We solve the problem using the common approach of only considering subgame perfect equilibria. Let consumer actions Ln, Lu, Bn, Bu and I denote leasing a new product, leasing a used product, buying a new product, buying a used product, and remaining inactive, respectively. We define customer  $\theta$ 's period- $t$  action vector under leasing as  $a_l^t(\theta) \doteq (l_n^t(\theta), l_u^t(\theta), i^t(\theta))$  and under selling as  $a_s^t(\theta) \doteq (b_n^t(\theta), b_u^t(\theta), i^t(\theta))$  where  $l_n^t, l_u^t, b_n^t, b_u^t$  and  $i^t$  are indicator variables corresponding to strategies Ln, Lu, Bn, Bu and I, respectively. Since remaining inactive is included in the consumer's action set, we have  $a^t(\theta)\mathbf{1}' = 1$  for all  $t$  and  $\theta \in [0, 1]$ . Finally, we let  $r^t \doteq (r_n^t, r_u^t)$  and  $p^t \doteq (p_n^t, p_u^t)$  denote the vectors of lease and sales prices for new and used products at time  $t$ .

### 2.3.1 Leasing Model

In this section, we focus on the steady-state equilibrium and solve for the optimal decisions of the leasing firm. This assumption of restricting attention to steady-state equilibria is commonly used in papers that consider an infinite-horizon leasing model in the durable goods literature (Hendel and Lizzeri, 1999b; Huang et al., 2001) and in the remanufacturing literature (Ferrer and Swaminathan, 2006). We begin by formulating and solving the consumer's utility maximization problem. The customer's action vector in period  $t$  is given by  $a_l^t(\theta) = (l_n^t(\theta), l_u^t(\theta), i^t(\theta))$ , with initial condition  $a_l^0(\theta) = (0, 0, 1)$  for all  $\theta \in [0, 1]$ . Since consumers enter each period without a product, the periods decouple; the consumer's action in the current period depends only on the payoff in the current period, which is independent of the consumers' previous actions and solely determined by the firm's period- $t$  decisions. Thus, consumer  $\theta$ 's optimal period- $t$  decision  $a_l^t(\theta)^*$  is determined by maximizing his period- $t$  net utility  $\Pi_\theta[a^t(\theta); r^t]$  subject to  $a_l^t(\theta)\mathbf{1}' = 1$ . Here,  $\Pi_\theta[(1, 0, 0); r^t] = u_n(\theta) - r_n^t$ ,  $\Pi_\theta[(0, 1, 0); r^t] = u_u(\theta) - r_u^t$  and  $\Pi_\theta[(0, 0, 1); r^t] = 0$ .

**Lemma 1** *In period  $t$ , the equilibrium consumer strategies have the following structure: Consumers in  $\theta \in (\theta_1, 1]$  always lease new products, consumers in  $\theta \in (\theta_2, \theta_1]$  always lease used products and consumers in  $\theta \in (0, \theta_2]$  remain inactive, where  $\theta_2 \leq \theta_1 \in [0, 1]$  such that*

$$u_u(\theta_2) - r_u^t = 0 \text{ and } u_n(\theta_1) - r_n^t = u_u(\theta_1) - r_u^t. \quad (1)$$

Turning now to the firm's problem, let  $L_n^t$  and  $L_u^t$  denote the quantity of new and used products leased by the firm at time  $t$ , respectively, and  $L^t \doteq (L_n^t, L_u^t)$ . The firm's profit in a given period depends on the current and previous period decisions:  $\Pi_l(L^{t-1}, L^t) = (r_n^t - c)L_n^t + (r_u^t - \beta_f)L_u^t - s_f(L_n^{t-1} - L_u^t) - s_f L_u^{t-1}$ . and  $L^t \geq 0$ ,  $L_u^t \leq L_n^{t-1} \forall t > 0$ .

**Proposition 1** *At the steady-state equilibrium, the optimal decisions are given as follows, where  $s_A(c, \delta, \beta_f) \doteq \frac{\beta_f - \delta c}{\delta}$  and  $s_B(c, \delta, \beta_f) \doteq \frac{\beta_f(1+\delta) + \delta(1-2c-\delta)}{2\delta}$ :*

Condition	$L_u^*$	$L_n^*$
$s_f \leq s_A(c, \delta, \beta_f)$	0	$\frac{1-c-s_f}{2}$
$s_A(c, \delta, \beta_f) < s_f < s_B(c, \delta, \beta_f)$	$\frac{\delta(c+s_f)-\beta_f}{2\delta(1-\delta)}$	$\frac{1-c-s_f+\beta_f-\delta}{2(1-\delta)}$
$s_B(c, \delta, \beta_f) \leq s_f$	$\frac{1-c-s_f-\beta_f+\delta}{2+6\delta}$	$\frac{1-c-s_f-\beta_f+\delta}{2+6\delta}$

Note that under Assumption A1, the firm prematurely disposes a fraction of the off-lease products ( $L_u^* < L_n^*$ ) if and only if  $s_f < s_B(c, \delta, \beta_f)$ . This threshold decreases in  $\delta$  and  $c$ , and increases in  $\beta_f$ : Premature disposal reduces the cannibalization of new product leases and avoids remarketing cost, but at the expense of foregoing revenue from off-lease products and generating a disposal cost. Thus, all else being equal, a low disposal cost, a high remarketing cost, and a high margin on the new product promote premature disposal. With respect to durability, the revenue effect dominates the cannibalization effect and high durability inhibits premature disposal.



### 2.3.2 Selling Model

In this section, we describe the model for the selling strategy and solve for its equilibrium. The model and analysis is similar to Huang et al. (2001), except that we incorporate disposal cost for customers and the firm, and focus on pure selling.

We start by formulating the consumer's problem. Consumer  $\theta$ 's action vector in period  $t$  is given by  $a_s^t(\theta) = (b_n^t(\theta), b_u^t(\theta), i^t(\theta))$ , with initial condition  $a_s^0(\theta) = (0, 0, 1)$  for all  $\theta \in [0, 1]$ . Under selling, since the consumer can keep his used product and the product lasts for two periods, a consumer's payoff in any given period depends on his action in the previous period and the prices in the current period (see Table 1). Thus, the dynamics are Markovian. As in the previous related literature, we restrict our attention to Markov perfect equilibria, which assumes that strategies only depend on the payoff-relevant history that is summarized by their current state (Fudenberg and Tirole, 1991).

**Table 1:** Net Utility Matrix  $\Pi_\theta[a_s^t(\theta); a_s^{t-1}(\theta), p^t]$  under Selling for Consumer  $\theta$  in period  $t$ .

$a_s^t(\theta)/a_s^{t-1}(\theta)$	$Bn$	$Bu$	$I$
$Bn$	$u_n(\theta) - p_n^t + p_u^t - \beta_c$	$u_n(\theta) - p_n^t$	$u_n(\theta) - p_n^t$
$Bu$	$u_u(\theta) - s_c$	$u_u(\theta) - p_u^t - s_c$	$u_u(\theta) - p_u^t - s_c$
$I$	$p_u^t - \beta_c$	0	0

Consumer type  $\theta$  has the following discounted net utility maximization problem given the price path  $\{p_t, t \geq 0\}$ :

$$V_\theta(a_s^0) = \max_{\{a_s^t(\theta), t \geq 1\}} \sum_{t=1}^{\infty} \rho^t \Pi_\theta[a_s^t(\theta); a_s^{t-1}(\theta), p^t].$$

Since the per period net utility is bounded and the strategy space is finite, the above problem can be solved by deriving the Bellman equation for consumer  $\theta$  by backward induction (Blackwell, 1965; Stokey and Lucas Jr, 1989). The net present value functions  $V_\theta^t[a_s^{t-1}(\theta), p^t]$  are a function of the consumer state  $a_s^{t-1}(\theta)$ , which completely

specifies the sufficient information, and are defined as follows:

$$V_{\theta}^t[a_s^{t-1}(\theta), p^t] = \max_{a_s^t(\theta) | a_s^t(\theta) \mathbf{1}' = 1} \Pi_{\theta}[a_s^t(\theta); a_s^{t-1}(\theta), p^t] + \rho V_{\theta}^{t+1}[a_s^t(\theta), p^{t+1}]. \quad (2)$$

Define the reaction function  $R_{\theta}^t[a_s^{t-1}(\theta), p^t] = a_s^t(\theta)^*$ , where  $a_s^t(\theta)^*$  is the solution to (2). Aggregating over all  $\theta$  yields the new and used product demand in period  $t$ ,  $S_n^t$  and  $S_u^t$ .

Recall  $p^t = (p_n^t, p_u^t)$  is the price vector at time  $t$ , where  $p_n^t$  is determined by the firm and  $p_u^t$  is the market clearing price for used goods, which is implicitly determined by equating supply and demand for used products. The optimal prices  $p_n^t, t \geq 0$  for a given customer demand path can be derived from the Bellman equation for the firm's problem. The equilibrium solution is therefore obtained by solving for the consumer and firm reaction functions of these coupled Bellman equations, subject to the market clearance conditions in every period. Huang et al. (2001) and Huang and Kuzyutin (2002) note that there is no known general procedure to solve coupled asymmetric Bellman equations, but that since a Markov-perfect equilibrium in the infinite time horizon is one in which all explicit time dependence has dropped out, it is appropriate to focus on an equilibrium in which all prices and aggregate consumer behaviors are constant in time. The fixed point in the strategy space that is associated with this equilibrium will be called the “focal point” following Huang et al. (2001). In order to find such an equilibrium, we need to solve the time-independent Bellman equations. The consumer's time-independent Bellman equation is given by

$$V_{\theta}[a_s(\theta), p] = \max_{a_s(\theta) | a_s(\theta) \mathbf{1}' = 1} \{\Pi_{\theta}[R_{\theta}[a_s(\theta), p]; a_s(\theta), p] + \rho V_{\theta}[R_{\theta}[a_s(\theta), p], p]\} \quad (3)$$

and the firm's problem reduces to the static optimization problem

$$\max_{S_n \geq 0} \Pi_s(S_n) = (p_n(S_n) - c)S_n,$$

where  $S_n$  is the aggregate demand for new products.

**Lemma 2** *There are at most four different consumer strategy patterns in equilibrium, for a given constant price vector  $p = (p_n, p_u)$ : Consumers in  $\theta \in (\Theta_1, 1]$  always buy new products (BnBn), consumers in  $\theta \in (\Theta_2, \Theta_1]$  buy a new product if their existing product has reached its end-of-life or continue to use their existing product (BnBu), consumers in  $\theta \in (\Theta_3, \Theta_2]$  buy used products from the secondary market in every period (BuBu) and consumers in  $\theta \in (0, \Theta_3]$  always remain inactive (II), where  $\Theta_3 \leq \Theta_2 \leq \Theta_1 \in [0, 1]$  and satisfy the following set of equations*

$$\begin{aligned} \frac{u_u(\Theta_3) - p_u - s_c}{1 - \rho} = 0, \quad \frac{u_u(\Theta_2) - s_c + \rho(u_n(\Theta_2) - p_n)}{1 - \rho^2} = \frac{u_u(\Theta_2) - p_u - s_c}{1 - \rho} \text{ and} \\ \frac{u_u(\Theta_1) - s_c + \rho(u_n(\Theta_1) - p_n)}{1 - \rho^2} = \frac{u_n(\Theta_1) - p_n + p_u - \beta_c}{1 - \rho}. \end{aligned} \quad (4)$$

For a given specification of consumer utility, the inverse demand functions can be calculated using (4). The supply of used products on the secondary market is given by  $1 - \Theta_1$  and the demand for them is given by  $\Theta_2 - \Theta_3$ . The market-clearing price is implicitly given by

$$1 - \Theta_1 = \Theta_2 - \Theta_3. \quad (5)$$

Since we are restricting our attention to a focal point where all firm and consumer behavior remains constant over time, in any given period, half of the consumers whose strategy is to play BnBu will use their existing product and the other half will have to buy a new product. This implies that the aggregate demand for new products ( $S_n$ ) in any period at the focal point is

$$S_n = 1 - \Theta_1 + \frac{\Theta_1 - \Theta_2}{2}. \quad (6)$$

**Proposition 2** *Under Assumption A1, the equilibrium per-period quantity of new products sold and the firm's per-period profit are*

$$\begin{aligned} S_n^* = \frac{\rho(2 - 2c - \beta_c - \rho s_c + \rho\delta) - s_c - \beta_c + \delta}{4(\rho + \delta(1 + \rho + \rho^2))} \text{ and} \\ \Pi_s(S_n^*) = \frac{(s_c + \beta_c - \delta - \rho(2 - 2c - \beta_c) + \rho^2(s_c - \delta))^2}{16\rho(\rho + \delta(1 + \rho + \rho^2))}. \end{aligned}$$

## 2.4 Comparing Leasing and Selling

In this section, we investigate the relative profitability and environmental impact of leasing and selling. For the remainder of the analysis, we assume that Assumption A1 holds. We also assume no discounting ( $\rho = 1$ ). Although comparisons with a general value of  $\rho$  are not difficult, this assumption simplifies our expressions and helps to isolate the effects of the disposal costs, product durability and remarketing costs. The insights from our analysis remain valid for values of  $\rho$  close to 1, which are realistic in practice.

**Measuring Environmental Impact.** The environmental impact of a strategy depends on the volume of products in each phase of the life cycle (production, use and disposal) and the per-unit impact of the product in each phase (White et al., 1999; Thomas, 2008). The former depends on the firm's production, remarketing and disposal strategy under leasing and on the firm's new production strategy in conjunction with consumer trading on the secondary market under selling. The latter depends on the product's environmental impact profile and can be found using a conventional life cycle analysis (U.S. EPA, 2008c). Products such as refrigerators, washers, televisions and automobiles have the majority of their environmental impact in the use phase (*high use impact products* for brevity), while products such as carpets, mattresses, cellphones and computers have the majority of their environmental impact in the production and disposal phases (*high non-use impact products* for brevity) (Bole, 2006; Quariguasi Frota Neto et al., 2007; MacLean and Lave, 1998; Intlekofer et al., 2009; Kuehr and Williams, 2003; Fishbein et al., 2000).

In steady-state, comparing the total life-cycle environmental impact of the two strategies reduces to comparing their per-period environmental impact. Under leasing, the per-period production and disposal volumes are both  $L_n^*$  and the per-period use volume is  $L_n^* + L_u^*$ . Under selling, the per-period production and disposal volumes are both  $S_n^*$ , and since products are only disposed of after two periods of use,

the per-period use volume is given by  $2S_n^*$ . Similar to Thomas (2008), we assume that environmental impact is independent of whether a product is leased or sold, or whether it is used or new. We also assume that the environmental impact due to consumer disposal is equal to that due to firm disposal. Under the above assumptions, the per-period environmental impact of a durable product is  $(i_p + i_d)L_n^* + i_u(L_n^* + L_u^*)$  and  $(i_p + i_d)S_n^* + 2i_uS_n^*$  under leasing and selling, respectively, where  $i_p$ ,  $i_u$  and  $i_d$  denote the environmental impact of one unit due to production, one period of use and disposal, respectively.

**Characterizing Relative Profitability and Environmental Impact.** In order to simplify the exposition and to focus on the differential effect of disposal costs, we assume  $\beta_f = \beta_c = 0$ . The nature of our insights remain the same for non-negative remarketing and transaction costs. We first present a special case,  $\delta = 0$ , as a building block in understanding the impact of different parameters.

**Lemma 3** *Let  $\delta = 0$ . If  $s_f = s_c$ , leasing and selling are equivalent. If  $s_f < s_c$ , leasing is strictly more profitable but has a higher environmental impact. Otherwise, selling is more profitable but has a higher environmental impact.*

When  $\delta = 0$ , the product is non-durable. Thus, the selling firm does not face any cannibalization from the secondary market. The only difference between leasing and selling is who incurs the disposal cost. If disposal is cheaper for the firm (or if the salvage value is higher) as compared to the consumer, leasing is more profitable. Since  $\delta = 0$ , there are no used products and the total environmental impact of leasing and selling are  $(i_p + i_u + i_d)L_n^*$  and  $(i_p + i_u + i_d)S_n^*$ , respectively. When the disposal cost is lower for the firm, the leasing firm produces a larger quantity of products and has a higher environmental impact.

This proposition suggests that it is sufficient to focus on the *effective* cost  $c + s$  to compare the relative profitability and the environmental impact of leasing and selling. Let  $c_l \doteq c + s_f$  and  $c_s \doteq c + s_c$  denote the effective cost (borne by the

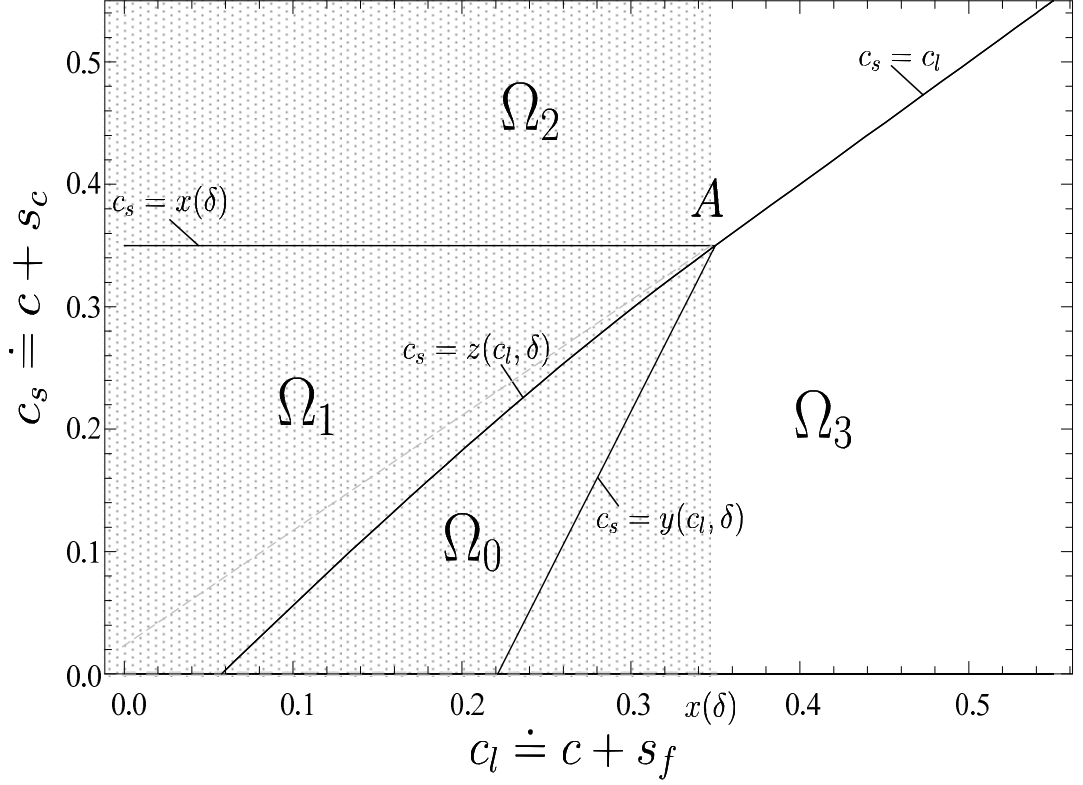
firm explicitly or implicitly) in leasing and selling, respectively. We find that the relative profitability and environmental impact of leasing and selling can indeed be summarized as a function of  $c_l$  and  $c_s$  (Figure 1). The thresholds defined in this figure are derived in Propositions 3 - 5.

**Proposition 3** *Let  $c_l > x(\delta) \doteq \frac{1-\delta}{2}$  (full remarketing is optimal). For  $c_l = c_s$ , leasing and selling are equivalent; for  $c_l < c_s$ , leasing is more profitable but has higher environmental impact; otherwise, selling is more profitable but has higher environmental impact.*

Recall we assume  $\beta_f = \beta_c = 0$  in this subsection. Then the condition  $s_f < s_B(c, \delta, \beta_f)$  derived in Proposition 1 for premature disposal to be optimal reduces to  $c_l < x(\delta) \doteq \frac{1-\delta}{2}$ . For  $c_l > x(\delta)$ , the leasing firm remarkets all off-lease products (full remarketing). Since with selling, no product is disposed of by consumers before its end of life, the only difference between the two strategies in this case is the difference in disposal cost (or equivalently, effective cost), as in Lemma 3. Thus, profits and environmental impact are equal if the disposal cost is the same for the firm and the consumer. If  $s_f < s_c$ , then  $c_l < c_s$ , and leasing is strictly more profitable. In addition, due to the lower effective cost, the firm produces (and disposes) a larger quantity of products. With full remarketing, this leads to a higher volume of products in use as well, and consequently, a higher total environmental impact. Similarly, if  $s_c < s_f$ , selling is more profitable and leads to a higher total environmental impact.

**Proposition 4** *Let  $c_l < x(\delta)$  (premature disposal is optimal). Selling and leasing are equally profitable for  $c_s = z(c_l, \delta) \doteq 1 + \delta - \sqrt{\frac{(1+3\delta)((1-\delta)(1-2c_l)+c_l^2)}{1-\delta}}$ , where  $z(c_l, \delta) < c_l$ . Leasing is more profitable if  $c_s > z(c_l, \delta)$ . Otherwise, selling is more profitable.*

Recall that with full remarketing, leasing is strictly more profitable if and only if  $s_c > s_f$  or if  $c_s$  is higher than the threshold  $c_l$ . With premature disposal, this



**Figure 1:** Characterization of the relative profitability and environmental impact of leasing and selling, where  $x(\delta) \doteq \frac{1-\delta}{2}$ ,  $y(c_l, \delta) \doteq \frac{c_l(1+3\delta)}{1-\delta} - 2\delta$  and  $z(c_l, \delta) \doteq 1 + \delta - \sqrt{\frac{(1+3\delta)((1-\delta)(1-2c_l)+c_l^2)}{1-\delta}}$ . Dots represent the area where premature disposal is optimal under leasing ( $c_l \leq x(\delta)$ ). Selling (leasing) is more profitable in region  $\Omega_0 \cup \Omega_3$  ( $\Omega_1 \cup \Omega_2$ ). The relative environmental impact in regions  $\Omega_0$  through  $\Omega_3$  is as follows: In  $\Omega_0$  and  $\Omega_1$ , selling has lower environmental impact due to production and disposal, and leasing has lower environmental impact due to use. In  $\Omega_2$ , selling has lower total environmental impact. In  $\Omega_3$ , leasing has lower total environmental impact. but environmentally superior only for products with high production and disposal impact in region  $\Omega_0$ . In region  $\Omega_1$ , leasing is more profitable and environmentally superior only for products with high use impact. Leasing is more profitable but environmentally inferior in region  $\Omega_2$  and selling is more profitable but environmentally inferior in region  $\Omega_3$ . In this figure,  $\delta = 0.3$ . Point A moves towards  $(0.5, 0.5)$  as durability decreases.

threshold is lower ( $z(c_l, \delta) < c_l$ ); the control that the leasing firm has over used products is exercised and reduces the impact of cannibalization, making leasing more competitive.

The conventional result in the durable goods literature is that for a monopolist, leasing is more profitable than selling, since under leasing a firm has control of the used products and does not face reduced demand due to consumers owning a used product (cf., Stokey, 1981; Bulow, 1982). Propositions 3 and 4 show that that if the consumers face a sufficiently lower disposal cost than the firm, the firm is better off not gaining control over the used products and selling is more profitable.

**Proposition 5** *Let  $c_l < x(\delta)$  (premature disposal is optimal). For  $c_s < y(c_l, \delta) \doteq \frac{c_l(1+3\delta)}{1-\delta} - 2\delta$ , leasing is strictly environmentally superior. For  $y(c_l, \delta) \leq c_s \leq x(\delta)$ , the total environmental impact in the use phase is lower under leasing and the total environmental impact in the non-use phases is lower under selling. For  $x(\delta) < c_s$ , selling is strictly environmentally superior.*

Consider the  $c_s = c_l$  case, which falls in the intermediate cost range  $y(c_l, \delta) < c_s < x(\delta)$  when the premature disposal condition holds. Since the leasing firm finds it optimal to prematurely dispose of used products, cannibalization is mitigated, and the leasing firm produces (and disposes) a larger volume than the selling firm ( $S_n^* < L_n^*$ ). Nevertheless, since the selling firm has no control over used products, while the leasing firm prematurely disposes of them, the volume of products in the use phase is higher for selling ( $2S_n^* > L_n^* + L_u^*$ ). Therefore, under this condition, the total environmental impact of leasing is lower for products with high enough impact in the use phase ( $i_u \gg i_p + i_d$ ) and selling is environmentally superior for products with high enough impact in the non-use phases ( $i_p + i_d \gg i_u$ ).

As the effective cost faced by the selling firm increases, the volume it produces (and disposes) decreases. When this cost is high enough ( $c_s > x(\delta)$ ), the production volume



under selling is low enough such that the total volume in use is also lower ( $2S_n^* < L_n^* + L_u^*$ ). Therefore, under the high cost range, selling is strictly environmentally superior.

As the effective cost faced by the selling firm decreases, the volume it produces (and disposes) increases. If this effective cost is low enough ( $c_s < y(c_i, \delta)$ ), the production and disposal volume under selling is higher than that under leasing ( $S_n^* > L_n^*$ ). In addition, since under selling, this larger volume of products remains in use for their entire life, the volume of products in the use phase is still higher under selling ( $2S_n^* > L_n^* + L_u^*$ ). Therefore, in this low cost range, leasing is strictly environmentally superior.

**When is Leasing (or Selling) the Win-Win Choice?** The environmental strategy literature has posited that there are many win-win business opportunities in practice that both increase profit and decrease environmental impact (Porter and Van Der Linde, 1995). Thus, it is interesting to ask when either leasing or selling can be a win-win choice. Combining Propositions 4 and 5, we see that leasing is both more profitable and has less environmental impact than selling only for high use impact products. This occurs when premature disposal is optimal and the effective cost under selling is neither too high nor too low relative to that under leasing (Region  $\Omega_1$ ). Interestingly, selling can also be a win-win strategy, this time for high non-use impact products. This occurs when premature disposal is optimal and the effective cost under selling is low enough relative to that under leasing (Region  $\Omega_0$ ). As the product durability increases, the threshold  $x(\delta)$  decreases. Thus, the area of regions  $\Omega_0$  and  $\Omega_1$  in Figure 1 decreases, i.e. win-win scenarios take place at lower values of disposal costs faced by the firm and the consumers for more durable products.

Consider products that have high use impact such as cars, washers, dryers, refrigerators and televisions (Bole, 2006; Quariguasi Frota Neto et al., 2007; MacLean

and Lave, 1998). It is reasonable to expect that a firm has better access to recyclers and lower collection or processing costs compared to an individual consumer for such bulky products. It is also reasonable to expect that for products that can be profitably disposed, a firm can recover a higher value from salvaging a unit than an individual consumer. In this case, the effective cost faced by a leasing firm will be lower than that faced by a selling firm. Thus, the conditions defining Region  $\Omega_1$  may hold for such products, in which case a leasing strategy will be both more profitable and environmentally superior.

Consider products such as computers, carpets or mattresses that have a high non-use impact (Intlekofer et al., 2009; Kuehr and Williams, 2003; Fishbein et al., 2000). For these products, consumers may face a lower disposal cost than a firm, due to stricter legislation for firms as compared to individual consumers. For example, federal law in the U.S. regarding hazardous electronic waste only applies for firms generating more than 220 lbs of such waste (U.S. EPA, 2008b). A firm may also voluntarily choose to recycle recovered units due to pressure from environmental groups, while consumers trash the product. For such products, the conditions defining Region  $\Omega_0$  may hold, in which case selling will be both more profitable and environmentally superior.

**Robustness of Insights to Assumptions.** We discuss the implications of relaxing some simplifying assumptions, focusing primarily on their effects on win-win scenarios.

*Effect of Remarketing Costs.* If we relax the assumption of zero remarketing costs, the structure of Figure 1 remains the same. Under leasing, the presence of a remarketing cost promotes premature disposal of off-lease units, which leads to a higher production and disposal volume and a lower use volume than the  $\beta_f = 0$  case. In contrast, under selling, the presence of a remarketing cost inhibits the secondary-market trade, prompting more consumers to hold onto their used product. This leads to a lower

demand for new products and consequently, results in lower production, disposal and use volumes than the  $\beta_c = 0$  case. Thus, introducing remarketing costs decreases the threshold  $y(c_l, \delta)$  and has an indeterminate impact on  $x(\delta)$ . It is reasonable to expect that a firm is more efficient at remarketing used products ( $\beta_f < \beta_c$ ), since it has economies of scale and is less likely to suffer from adverse selection as compared to consumers (Huang et al. 2001). In this case, the relative profitability of leasing increases ( $z(c_l, \delta)$  decreases) when there are remarketing costs.

*Effect of Differential Disposal Impact.* We assumed that the disposal impact is independent of who disposes the product. In practice, firms may have better access to environmentally superior alternatives (e.g. recycling vs landfilling). All else being equal, the only resulting change will be a reduction in the environmental impact due to disposal under leasing. Therefore, the threshold  $y(c_l, \delta)$  will be higher and the area where selling is a win-win strategy (Region  $\Omega_0$ ) will shrink, or may not exist.

*Effect of Remarketing Mechanism under Leasing.* We restricted our attention to a pure leasing strategy where off-lease products are again leased. If the leasing firm endogenously chooses between leasing and selling off-lease units, the firm will choose to sell them only if the consumers enjoy a lower disposal cost ( $c_s < c_l$ ). This results in a lower effective cost under leasing, which in turn increases both the profitability and the total environmental impact of leasing (thresholds  $z(c_l, \delta)$  and  $y(c_l, \delta)$  are lower). Therefore, the area of region  $\Omega_1$  (where leasing is win-win) is larger, and the area of  $\Omega_0$  (where selling is win-win) is typically smaller. Finally, when  $c_s < c_l$  and full remarketing is optimal, the profits and the total environmental impact are equal under both strategies. Thus, allowing the firm to endogenously choose between leasing or selling off-lease units makes leasing more profitable, but at the expense of its total environmental impact.

## 2.5 Conclusions

*Is leasing greener than selling?* Articles in industrial ecology and environmental strategy have answered in the affirmative, and have influenced firms, public entities and environmental groups. Whether leasing is greener *and* more profitable is not the concern of the industrial ecology literature, while the environmental strategy literature promotes the win-win argument - that many strategies that are environmentally superior are also more profitable. With this study, we aim to provide guidance to firms on the viability of promoting leasing as the “greener” strategy. As profit-maximization is the primary objective for firms, we also identify the locus of green and profitable strategies.

To this end, we develop infinite-horizon, sequential dynamic models of pricing, remarketing and disposal for durable products put on the market via leasing or selling by a profit-maximizing monopolist. We characterize the optimal quantity of new and used products observed in equilibrium, and calculate the total volume of products in each life cycle phase (production, use and disposal) under each strategy to compare their total environmental impact. Based on our analysis, we find that the magnitude of the disposal cost, the differential in the disposal costs faced by the firm and consumers, and the environmental impact profile of the product (whether the majority of the impact is in the use phase or the production and disposal phases) are the main drivers of relative profitability and environmental impact (Figure 2). The insights obtained from our analysis are of relevance to manufacturers, environmental groups, and policy makers, and are discussed below.

*The remarketing level is not a good proxy for environmental impact.* Recall the main argument for the environmental superiority of leasing is that since the firm owns the off-lease units, it has an incentive to remarket them (Hawken et al., 1999; Lifset and Lindhqvist, 2000; Fishbein et al., 2000; Mont, 2002; Robert et al., 2002). In contrast, Ruth (1998) and Lawn (2001) argue that leasing may be worse for the

	<i>Premature Disposal</i>		<i>Full Remarketing</i>
	<i>High Non-use Impact</i>	<i>High Use Impact</i>	
<i>Moderately Lower Firm Disposal Cost</i>	P = Lease E = Sell <b>X</b>	P = Lease E = Lease ✓	P = Lease E = Sell <b>X</b>
<i>Moderately Lower Consumer Disposal Cost</i>	P = Sell E = Sell ✓	P = Sell E = Lease <b>X</b>	P = Sell E = Lease <b>X</b>

**Figure 2:** When is a marketing strategy greener and more profitable? Profit-maximizing and environmentally superior strategies are denoted by “P=” and “E=”, respectively. Premature disposal and full marketing are options available to the leasing firm and are driven by the magnitude of the firm’s disposal cost.

environment due to the firm’s ability to prematurely dispose recovered off-lease products. We find that leasing may be *less green than selling despite full remarketing*, and *greener despite premature disposal*. Market effects (demand volume, use duration) account for these results. When the firm’s disposal cost is high, but lower than the consumer’s, the leasing firm fully remarkets, but leasing has higher environmental impact: Full remarketing may reduce but does not eliminate the incentive for the firm to produce a larger volume of products than with selling to exploit this cost advantage. The larger sales volume in conjunction with full remarketing translates into higher environmental impact. In contrast, when the disposal cost is low enough to make premature disposal optimal, leasing can be greener for high use impact products despite premature disposal. The reason is that premature disposal reduces the contribution of the use phase to the life-cycle environmental impact. We conclude that the remarketing level is not a complete indicator of a firm’s total environmental impact.

*Selling may be more profitable.* We identify asymmetry in disposal cost as the primary driver of the relative profitability of the two strategies. When the firm’s disposal

cost is higher, selling is more profitable because it transfers disposal responsibility to the consumer. This finding complements the recent literature that identifies settings where selling may dominate leasing (Bucovetsky and Chilton, 1986; Desai and Purohit, 1998, 1999; Desai et al., 2004; Bhaskaran and Gilbert, 2005). It is not unusual for the firm’s disposal cost to be higher. Consider Interface’s Evergreen Lease. Commercial carpeting, while durable, does not lend itself to reuse and only some of the material can be recycled. Thus, by committing itself to collecting and (partially) recycling the carpet, Interface effectively increased its disposal cost significantly relative to local landfilling by its customers. As our results show, selling is more profitable in this case, and a publicly traded firm such as Interface would find it difficult to deviate from profit maximization as its primary objective. Thus, despite originally being championed at the highest levels of the company, the leasing program was phased out, although the recent spike in oil prices, which makes recycled nylon competitive with virgin nylon, gave the company hope that it could be reintroduced (Ferguson and Plambeck, 2008). Interestingly, *selling can even be a win-win choice, but only for high non-use impact products*. This occurs when the volume put on the market is higher with leasing despite a lower consumer disposal cost.

*Leasing may be more profitable, but less green.* The very reason leasing is more profitable may be the reason why it is not greener. In our model, disposal cost asymmetry in favor of the firm makes leasing more profitable, but also drives volume up, resulting in higher total life-cycle environmental impact when full remarketing is optimal. Therefore, skepticism vis-a-vis claims by firms who lease their products that this is the environmentally superior strategy is warranted. We conclude that to judge the environmental impact of a strategy, a comprehensive assessment, which takes market effects throughout the product life cycle into account, is needed.

*Leasing can be a win-win choice for high use-impact products.* When premature disposal is optimal, the volume of products in the use phase is reduced. Thus, even

when leasing leads to a higher volume put on the market, the total environmental impact of this strategy can be lower for those products that have a high impact during the use phase. For example, leasing photocopiers for Xerox may well be a win-win choice, since photocopiers have high use impact (McIntyre et al., 1998; Sundin et al., 2000), Xerox remarkets only a portion of off-lease products, and enjoys a higher salvage value than consumers, since it harvests spare parts and recyclable materials from off-lease units that are not remarketed.

Motivated by the claims in the industrial ecology and environmental strategy literature, Interface adopted leasing as an environmentally superior business model. Since Interface has access to technologies which can be used to recycle carpet profitably, it faces a lower disposal cost. However, leasing may lead to a larger quantity of products being produced compared to selling and be environmentally inferior. This might not hold if a firm decides to dispose units using an alternative with much lower impact as compared to the consumers (e.g. recycling versus landfilling). Therefore, Interface can improve the environmental performance of their leasing strategy by attempting to reduce the environmental impact of their recycling technologies. Thus, a better understanding of the total environmental impact, and not just remarketing and disposal efforts is required, before claiming to be greener to avoid being accused of greenwashing.

*Leasing is a hard sell.* As discussed in §2.1, several policy-making groups such as the U.S. Environmental Protection Agency, the state of Minnesota and the New York City Government are actively promoting leasing as the greener alternative. In this study, we provide two main insights for such policy-makers: First, leasing is not always greener than selling, and care must be taken to avoid blanket statements about one strategy being environmentally superior over the other. Second, even if leasing is greener, firms may not have an incentive to adopt it as selling may be more profitable precisely in this case. A better understanding of the drivers of the relative

profitability of leasing and selling can enable the design of incentives to encourage the adoption of the environmentally superior strategy.

To summarize, we offer new insights into a firm's lease versus sell decision, and provide an analytical comparison of the total environmental impact (based on total volumes produced, used, and disposed) of each strategy. We show that our qualitative insights are robust to a number of assumptions such as the existence of remarketing costs, asymmetry in the environmental impact of disposal, and the choice of the remarketing strategy. Thus, we add to the important knowledge base on product leasing that will benefit not only managers, but also environmental groups and policy makers. We hope that our study will promote more research exploring the impact of marketing strategies on the environmental performance of the firm.



## CHAPTER III

### THE EFFECT OF REMANUFACTURING ON THE PERCEIVED VALUE OF NEW PRODUCTS

#### *3.1 Introduction*

Many firms, from industrial equipment manufacturers (e.g., Xerox, Caterpillar) to consumer electronics manufacturers (e.g., HP, Apple, Bosch Tools), sell new and remanufactured versions of their products. Used products (or cores) that can be remanufactured are acquired by Original Equipment Manufacturers (OEMs) from several different sources: commercial returns, repair or warranty returns, flexible return policies, trade-ins, or end-of-life take-back. The residual value in these cores and the cost savings from remanufacturing may provide OEMs with an incentive to remanufacture their products. Nevertheless, the decision to pursue remanufacturing is not a simple one. Remanufactured products are generally sold at lower prices and they may compete with the OEM's new products. In fear of such cannibalization of new product sales, some OEMs choose not to sell remanufactured products (e.g., Cisco, Wall Street Journal, 2009). However, if an OEM chooses not to remanufacture, third-party competitors may actively collect and remanufacture used products originally sold by the OEM, creating competition for the OEM's new products. For example, HP does not remanufacture printer cartridges and faces competition from third-party competitors who sell remanufactured HP printer cartridges (Hewlett-Packard, 2009). Thus, for an OEM, remanufacturing may appear better than allowing a third-party to remanufacture its products.

On the other hand, remanufactured products may negatively influence the perceived value of new products, which in turn may affect an OEM's remanufacturing

decision. Consider the following quotes from Apple’s online discussion forum: “...Just where are the refurbished iPhones coming from? Is Apple getting enough returns so they can resell them...” (CNET, 2007), “...Apple is really ruining the reputation that they built...” (Apple.com Online Forum, 2008b). These concerns may arise from consumer perceptions that an OEM is remanufacturing because it is receiving failure and warranty returns due to the low quality of new products. Consumers may also value a remanufactured product sold by a third party lower than one sold by the OEM. Consider the following quote: “...why would you buy a [remanufactured] iPhone from an untrusted source or seller on ebay? Buy a refurbished iPhone from Apple...” (Apple.com Online Forum, 2008a). These concerns may be driven by consumer expectations that the OEM has a better reputation or superior remanufacturing technology. Motivated by these observations, our goal in this study is to investigate whether remanufacturing by an OEM or a third-party remanufacturer affects the perceived value of new products and how an OEM should consider this effect before pursuing remanufacturing and other competitive strategies against third-party remanufacturers.

To this end, we focus on consumer products and experimentally investigate the effect of remanufactured products and the identity of the remanufacturer (i.e., OEM or a third-party remanufacturer) on the perceived value of new products. In our experiment, we find that the perceived value of the OEM’s new product decreases when the OEM sells remanufactured products, which may be explained by consumers’ quality concerns regarding remanufactured products spilling over to the new products. This result is also similar to the research on product-line extensions that studies the effect of low-end products on the perceived value of the existing product (Randall et al., 1998; Kim et al., 2001). Thus, our results suggest that although remanufactured products sold by an OEM are physically and functionally the same as new products, they may have the same effect on the perceived value of the new product as low-end

products.

Interestingly, this effect reverses in our experiment; when the remanufactured products are offered by third-parties, the perceived value of new products increases in the presence of third-party remanufacturers. This reversal may be due to the following reason: Since the products are remanufactured by the third party, quality concerns about the remanufactured products may not be attributed to the OEM's new products. Moreover, consumers may perceive a third party establishing a business based on remanufacturing the OEM's new products as a signal of the new product's high quality.

Based on these experimental insights, we develop an analytical model to provide a general framework for determining an OEM's optimal strategy for different types of consumer products for which the changes in perceived value of new products may vary. Our model characterizes conditions under which it is profitable for an OEM to let a third party remanufacture its products, or preempt a third-party remanufacturer by pursuing remanufacturing or collection of used products. These strategic and competitive decisions in the remanufacturing context have been investigated in the closed-loop supply chain literature (see Atasu et al., 2008a and Guide and Van Wassenhove, 2009 for recent overviews). In particular, Majumder and Groenevelt (2001); Debo et al. (2005); Ferrer and Swaminathan (2006); Ferguson and Toktay (2006); Jin et al. (2007); Atasu et al. (2008b), and Agrawal et al. (2009) have studied the effect of cannibalization and external competition from a remanufactured product on an OEM's remanufacturing and competitive strategies. This stream of literature concludes that the entry of a third-party remanufacturer is detrimental for an OEM and suggests that it may be profitable for an OEM to remanufacture or collect cores to preempt third-party remanufacturers (Ferguson and Toktay, 2006).

However, this entire stream of literature assumes that the presence of remanufactured products does not have an effect on the perceived value of new products.

To the best of our knowledge, this is the first study to investigate this effect and find that the presence of remanufactured products may have an effect on the perceived value of new products. We analytically show that this has a significant impact on an OEM's optimal remanufacturing strategy in the presence of competition from a third-party remanufacturer. In particular, in contrast to the existing literature, we show that preempting such competitors through remanufacturing or collecting cores may be detrimental and an OEM may instead benefit from allowing them to remanufacture its products. Our results also provide support to some strategies observed in practice that may not be explained by existing literature. For example, Cisco does not remanufacture or preempt third-party remanufacturers (Wall Street Journal, 2009), Apple remanufactures but only sells remanufactured products online (Apple, 2009b), and HP does not remanufacture printer cartridges and actively tries to reduce the perceived value of the remanufactured cartridges sold by third-party competitors through advertising (Hewlett-Packard, 2007; Hewlett-Packard, 2009).

Our work also contributes to the emerging stream of behavioral research in closed-loop supply chains. Guide and Li (2009) conduct eBay experiments and find that on average, remanufactured products are purchased at lower prices than new products. Subramanian and Subramanyam (2009) use purchase data from eBay and find that seller reputation and product categories play an important role in the price differences between new and remanufactured products. Quariguasi Frota Neto (2008) explores the effect of the new product price as a reference price in the remanufacturing context and Ovchinnikov (2009) investigates the effect of the discount on remanufactured products on the purchasing behavior of the consumers. However, all of these papers only focus on how consumers value remanufactured products. In contrast to this literature, we focus on investigating the effect of remanufacturing on the perceived value of new products.

The remainder of the essay is structured as follows: In §3.2 we experimentally

investigate the effect of remanufactured products on the perceived value of new products. We outline the development of our analytical model in §3.3. We model and analyze an OEM’s competitive strategies in the presence of remanufacturing competition in §3.4. In §3.5 we discuss the managerial insights from our results, and conclude with a discussion of directions for future research. All proofs are provided in the Appendix.

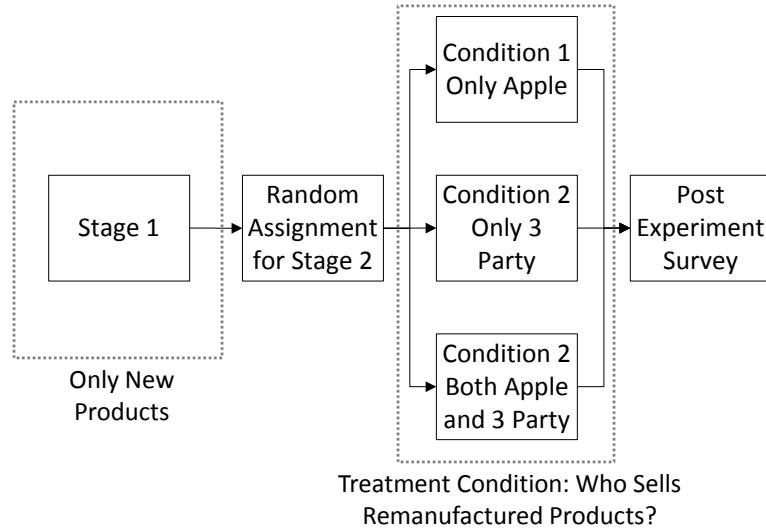
## ***3.2 The Experiment***

To investigate the effect of remanufactured products on the perceived value for new products, we conducted an experiment consisting of two stages that took place three weeks apart. In our experiment, we use willingness to pay as a proxy for perceived value. In Stage 1, the willingness to pay for a new product in the absence of remanufactured products is established. In Stage 2, the willingness to pay for the same new product in the presence of remanufactured products is established. A within-subject comparison of the willingness to pay for the new product between Stages 1 and 2 helps us to investigate the effect of remanufactured products on the willingness to pay for new products. We describe the experimental design and procedure in §3.2.1, the measures and analyses in §3.2.2, and the key results in §3.2.3.

### **3.2.1 Design and Procedure**

To examine the effect of remanufactured products on the willingness to pay for new products, we conducted an experiment involving 123 student participants at a large U.S. university who participated for partial course credit. Forty-one percent of the participants were female and the average age of the participants was 21.2 years (19-32 years). The experiment was conducted using Apple iPods. They were chosen as an example of consumer products that are familiar to the study participants. The experiment consisted of two stages as described below and outlined in Figure 3.

**Stage 1.** In Stage 1, the willingness to pay for a new product in the absence of



**Figure 3:** Process Flow Diagram for the Experiment, where Stage 1 and 2 were conducted 3 weeks apart.

remanufactured products was established using a full-factorial judgment task (Green and Srinivasan, 1990; Kivetz et al., 2004) involving three attributes: price, memory size, and seller, which were selected as relevant attributes based on informal discussions with subjects from the same subject pool. These discussions were also used to collect information regarding the relevant range of attribute levels, which was next benchmarked against actual market information from Apple’s website. Using three price levels (\$99, \$149, \$199), two memory sizes (8 GB, 16 GB), and two sellers (Apple.com, MP3Playerstore.com), twelve iPod profiles (e.g., iPod, 8GB, \$149, Apple.com) were constructed (Hair et al., 2009).

Before asking the participants to judge the 12 iPod profiles, one profile at a time, they were informed that they were about to be presented with 12 new iPods that were described on price (\$99, \$149, \$199), memory size (8 GB, 16 GB), and sellers (Apple.com, MP3Playerstore.com). Participants were asked to focus on these three characteristics and to assume that all 12 iPods are comparable on any of the other characteristics they might normally take into consideration (Kivetz et al., 2004). Participants were asked to consider the iPod profiles and indicate the likelihood that

they would purchase each of them (0% - 100%) (Hair et al., 2009). The profiles were randomized and no order effects were found. The average<sup>1</sup> willingness to pay for a new iPod under this stage is denoted by  $v_n(x)$  (where  $x$  denotes the absence of remanufactured products).

**Stage 2.** Three weeks after Stage 1, the second stage of the experiment was conducted. A search for announcements in the major business wire services shows that no new iPod campaign, major price change or generation was launched during the time period between the Stages 1 and 2 (March 31, 2009 - April 23, 2009). Thus, any changes in the willingness to pay for new products between the Stages 1 and 2 can be attributed to the presence of remanufactured products in Stage 2.

As before, a full-factorial judgment task was employed to assess the willingness to pay for a new product in the presence of remanufactured products. To accomplish this, in addition to the three price levels (\$99, \$149, \$199), two memory sizes (8 GB, 16 GB), and two sellers (Apple.com, MP3Playerstore.com) used in Stage 1, a fourth attribute, type of product, consisting of two levels (new, refurbished) was added. Based on these attributes and levels, 24 iPod profiles were created: 12 new iPods that were identical to those studied in Stage 1 and 12 remanufactured iPods.

In order to examine the effect of remanufactured products on the perceived value of new products and investigate how this effect may depend on who sells the remanufactured product, we created three between-subject conditions. Every participant was randomly assigned to one of the three conditions. Every participant was presented with all 24 iPod profiles, one profile at a time. Based on their condition, participants were asked to provide 18 (Conditions 1 and 2) or 24 (Condition 3) judgment scores.

*Condition 1.* This condition was designed to represent the case where remanufactured products are only sold by the OEM. Participants in this condition were informed

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<sup>1</sup>Since no interaction effects were observed, all experimental results hold at the individual levels and we only report average values. Details at the individual level are available on request.

that “As part of company policy, Apple sells refurbished<sup>2</sup> electronics such as iPods. Refurbished iPods are not available from third parties, such as MP3PlayerStore.com.” Participants provided a judgment score for the twelve new iPods and the six remanufactured iPods sold through Apple. We denote the average willingness to pay for new and remanufactured products under this condition by  $v_n(o)$  and  $v_r(o)$ , respectively.

*Condition 2.* This condition was designed to represent the case where remanufactured products are only sold by the third-party remanufacturer. Participants were informed that “As part of company policy, Apple does not sell refurbished electronics such as iPods. Refurbished iPods can be purchased from third parties, such as MP3PlayerStore.com.” In this condition, participants provided a judgment score for the twelve new iPods and the six remanufactured iPods sold through MP3PlayerStore.com. We denote the average willingness to pay for new and remanufactured products under this condition by  $v_n(3p)$  and  $v_r(3p)$ , respectively.

*Condition 3.* The third condition was designed to check if the effects of remanufactured products on the willingness to pay for new products observed from the previous two conditions are systematic. Participants in Condition 3 were informed that both Apple and MP3PlayerStore.com sell remanufactured products and they were asked to provide judgment scores for the 12 new and 12 remanufactured products sold by Apple and MP3PlayerStore.com. We denote the average willingness to pay for new and remanufactured products under this condition by  $v_n(b)$  and  $v_r(b)$ , respectively.

As in Stage 1, before asking participants to judge the iPod profiles, they were informed that they were to be presented with 24 iPods that were described on price (\$99, \$149, \$199), memory size (8 GB, 16 GB), sellers (Apple.com, MP3Playerstore.com) and type (new, refurbished). Using the description available on the Apple web site,

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<sup>2</sup>Since Apple uses the term “refurbished” we use the same term in our experiment. For the rest of the discussion, in line with the existing closed-loop supply chain literature, we use remanufacturing and refurbishing interchangeably to denote any kind of activity that brings a used or returned item to a like-new condition for resale purposes in the original product market.



participants were explained that “Refurbished products are pre-owned products that undergo a stringent refurbishment process prior to being offered for sale.” In each condition, the remanufactured product was sold by the party that remanufactured the product. Participants were further asked to focus on these four characteristics and to assume that all iPods are comparable on any of the other characteristics they might normally take into consideration. Participants were asked to consider the iPod profiles and indicate the likelihood that they would purchase each one of them (0% - 100%) (Hair et al., 2009). The profiles were randomized and no order effects were found.

To match the responses of Stage 1 and Stage 2 at the individual level, participants provided the last four digits of their social security number during both stages. Furthermore, in order to gain a better understanding of consumer concerns or perceptions of remanufactured products, the participants were also asked to answer open-ended questions regarding remanufactured products after Stage 2. A representative subsample of their responses is provided in the appendix §A4.

### 3.2.2 Experimental Analysis

To determine the willingness to pay for the new and remanufactured products, we first confirmed that the product profiles in Stages 1 and 2 were at least weakly ordered and the valuation of a product profile was confirmed to be represented by an additive combination of separate valuations for the individual attribute levels (i.e., no significant interaction effects were found). Next, the overall judgments in each stage, for the new and refurbished iPods were decomposed into valuations for each attribute level using dummy variable regressions. The analyses were conducted at the individual level for the new and remanufactured products in each stage as follows:

$$Y_{ij} = \beta_0 + \beta_1 P_{ij}^{\$149} + \beta_2 P_{ij}^{\$199} + \beta_3 M_{ij}^{16GB} + \beta_4 S_{ij}^{OEM} \quad (7)$$

where  $y_{ij}$  is an individual  $i$ 's overall likelihood of purchasing profile  $j$ ,  $P_{ij}^{\$149}$  is a

dummy variable that is 1 if the price level of profile  $j$  is \$149 and 0 otherwise,  $P_{ij}^{\$199}$  a dummy variable that is 1 if the price level of profile  $j$  is \$199 and 0 otherwise,  $M_{ij}^{16GB}$  is a dummy variable that is 1 when profile  $j$  has a memory size of 16GB and 0 otherwise,  $S_{ij}^{OEM}$  is a dummy variable that is 1 when profile  $j$  is sold by the OEM and 0 otherwise.  $\beta_0$  is the constant and represents the likelihood of purchasing the baseline iPod (\$99, 8GB, sold by the third party),  $\beta_1$  represents the change in the likelihood when the price increases from \$99 to \$149,  $\beta_2$  reflects the change in likelihood when the price increases from \$99 to \$199,  $\beta_3$  represents the change in likelihood when the memory size increases from 8GB to 16GB,  $\beta_4$  reflects the change in likelihood when the OEM sells the iPod instead of the third party. Based on these estimates, the overall likelihood of each iPod can be predicted in an additive manner. The correlation between the observed overall likelihood and this predicted likelihood was found to be generally high (Pearson's  $R > 0.96$ ,  $p < .001$ , Kendall's Tau  $> .93$ ,  $p < .001$ ), suggesting that the additive model is an accurate representation of the consumer evaluation process.

In order to estimate the willingness to pay for the new product in Stage 1, the willingness to pay for the new product and the remanufactured products in Stage 2, we determine the price point at which a consumer is indifferent between purchasing a product or not, i.e. our willingness to pay estimates represents the maximum willingness to pay (see details in Appendix §A3). Next, differences in willingness to pay for new products between Stage 1 and Stage 2 and willingness to pay for remanufactured products in Stage 2 are examined at the individual level—within-subjects—using paired samples t-tests.

**Table 2:** The effect of remanufactured products on the willingness to pay for the new products.

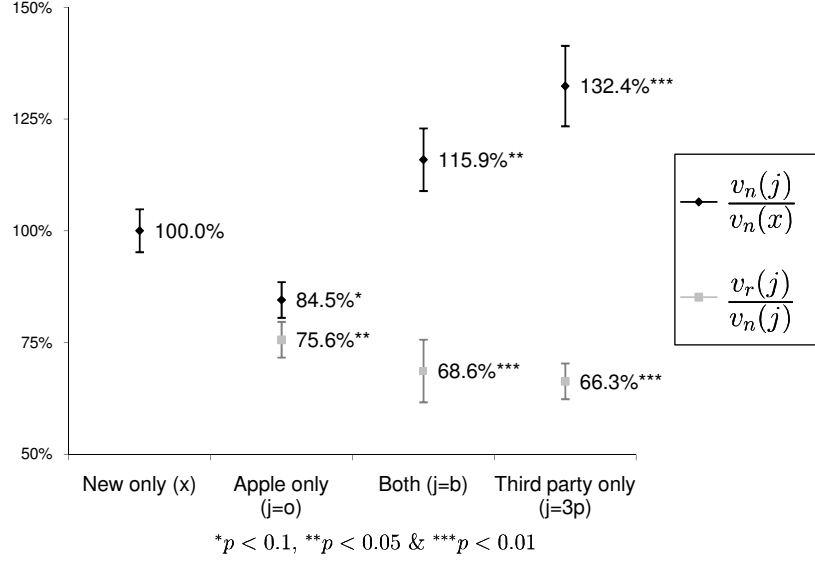
	Stage 1: New	Stage 2: New & Remanufactured		
Remanufactured sold by	None ( $j = x$ )	Condition 1 Apple only ( $j = o$ )	Condition 2 3P only ( $j = 3p$ )	Condition 3 3P & Apple ( $j = b$ )
$v_n(j)/v_n(x)$	100%	84.5% $t(40) = -1.72, p < .10$	132.4% $t(43) = 3.07, p < .01$	115.9% $t(34) = 2.10, p < 0.05$
$v_r(j)/v_n(j)$		75.6% $t(40) = 3.58, p < .01$	66.3% $t(45) = 4.33, p < .01$	68.6% $t(34) = 4.28, p < .01$

### 3.2.3 Experimental Results

The results from our experiment are summarized in Table 2 and Figure 4, and the estimates of the regression coefficients at the aggregate level are provided in the Appendix §A5. To understand the effect of remanufactured products on the willingness to pay for new products, we benchmark  $v_n(o)$ ,  $v_n(3p)$  and  $v_n(b)$  against the willingness to pay for new products in the absence of remanufactured products,  $v_n(x)$ . Similarly, the willingness to pay for remanufactured products under each condition,  $v_r(j)$  is benchmarked against that for the new product in the same context,  $v_n(j)$ . Results 1-3 summarize the main findings from our experiment.

*Result 1. Willingness to pay for a remanufactured product is significantly lower than that for a new product,  $v_r(j)/v_n(j) < 1$ , in all three conditions,  $j = o, 3p, b$ .*

Consistent with expectations, we find that the willingness to pay for a remanufactured product is lower than that for a new product, for each individual condition (see Table 2), as well as across the three conditions ( $t(119) = 6.72, p < .01$ ) in our experiment. This result validates the modeling assumption in the existing analytical literature (Debo et al., 2005; Ferguson and Toktay, 2006; Atasu et al., 2008b) and complements recent research that also finds support for this result using different experimental and empirical approaches (Guide and Li, 2009; Subramanian and Subramanyam, 2009). However, none of these papers differentiate between the willingness to pay for a remanufactured product sold by the OEM and one sold by a third-party remanufacturer. In contrast, in our next result, we find that the willingness to pay for remanufactured products depends on the identity of the firm that remanufactures



**Figure 4:** The effect of remanufactured products on the willingness to pay for new products, where black markers denote  $v_n(j)/v_n(x)$ , which is the relative change in willingness to pay for new products due to the presence of remanufactured products and gray markers denote  $v_r(j)/v_n(j)$ , which is the willingness to pay for a remanufactured product relative to a new product under the same condition, for all  $j = \{o, 3p, b\}$ .

it.

*Result 2. Willingness to pay for a remanufactured product relative to a new product,  $v_r(j)/v_n(j)$ , is significantly higher when the remanufacturing is carried out by the OEM as opposed to when it is carried out by a third-party remanufacturer, i.e.,  $v_r(o)/v_n(o) > v_r(3p)/v_n(3p)$ .*

As in the existing literature (Debo et al., 2005; Ferguson and Toktay, 2006; Atasu et al., 2008b), Result 2 considers the willingness to pay for a remanufactured product relative to a new product and highlights the importance of consumer perceptions in a remanufacturing context. Although the same neutral description of the remanufacturing process was provided in both conditions, an independent samples t-test shows that our subjects clearly had a lower relative willingness to pay for the third party's remanufactured product as compared to the OEM's remanufactured product ( $t(85) = 4.96, p < .01$ ). The OEM in our experiment, Apple, has a good reputation

for quality. This suggests that subjects are likely to associate the quality of remanufactured products with their seller, as observed by Subramanian and Subramanyam (2009) in the context of remanufactured products sold on eBay. While this result seems to suggest that remanufacturing may be more attractive for the OEM, our next result demonstrates that remanufacturing can also be detrimental for the OEM.

*Result 3. When the OEM sells the remanufactured products, the willingness to pay for a new product is significantly lower than that in the absence of remanufactured products,  $v_n(o) < v_n(x)$ . In contrast, when the third-party remanufacturer sells remanufactured products, willingness to pay for a new product is significantly higher than that in the absence of remanufactured products,  $v_n(x) < v_n(3p)$ .*

The above result shows that the willingness to pay for new products changes in the presence of remanufactured products in our experiment. Interestingly, although subjects in all conditions were provided the same information regarding the remanufacturing process, we find that the direction of change in their willingness to pay for new products is different based on who remanufactures and sells the remanufactured products. While consumer willingness to pay for the OEM’s new product decreases when the OEM remanufactures, it increases when a third party remanufactures (see Table 2).

What may cause this difference? The negative effect of the OEM-remanufactured products on the perceived value of new products in our experiment may be attributed to the well-established “similarity hypothesis” which poses that a newly introduced product affects the perceived value of existing similar products (Tversky, 1972). When the OEM sells new and remanufactured products, both may be perceived as relatively similar by the consumers: On one hand, consumer perceptions of the remanufactured product may benefit from consumer perceptions of the OEM’s expertise with producing the new product. As suggested by Result 2, the relative perceived value of the OEM-remanufactured product as compared to a new product is indeed higher

than that of the third-party’s remanufactured product. On the other hand, quality concerns about the remanufactured product may spillover to the new product (cf., Randall et al., 1998; Kim et al., 2001). Consumers may associate OEM remanufacturing with failure and warranty returns (CNET, 2007) or other quality concerns in the new products (also see subject responses in Appendix §A4). This may explain why the perceived value of new products is degraded by the presence of remanufactured products sold by the OEM in our experiment.

However, when the remanufactured product is sold by the third party, spillover effects between remanufactured and new products are expected to be limited. Consumers may think that it is difficult for the OEM to control what third-parties do with its product and, consequently, quality concerns about remanufactured product may not be attributed to the OEM’s new products. Consumers may also perceive a third party establishing a business remanufacturing the OEM’s products as a signal of high quality of the OEM’s new products. In addition, Result 2 suggests that the relative willingness to pay for a remanufactured product may be lower when it is sold by the third party. In this setting, the third-party-remanufactured product may represent an asymmetrically dominated product option, i.e. an option (buying a remanufactured product) which is dominated by one option in the set (buying a new product) but not by another (not buying a product). It has been shown in other contexts that adding such an option increases the probability of choosing the option that dominates it (buying a new product) (Huber et al., 1982). This may explain why the perceived value of the new product increases in the presence of third-party remanufactured products in our experiment.

Finally, an investigation of our third condition ( $j = b$ ) shows that the effect of remanufactured products on the perceived value of new products is systematic in our experiment. This can be observed in Figure 4 (by comparing Condition  $j = b$  with the Conditions  $j = o$  and  $j = 3p$ ): the effect of remanufactured products on new products

averaged across the cases where either the OEM ( $j = o$ ) or third party ( $j = 3p$ ) sell remanufactured products, is similar to that found when both sell remanufactured products ( $j = b$ ). It is also interesting to note that when remanufactured products are sold by both firms in our experiment, the positive effect of the remanufactured products sold by the third party dominates the negative effect of the remanufactured products sold by the OEM.

### 3.3 *The Model*

In this section, we outline the development of our analytical model which investigates an OEM's optimal remanufacturing and competitive strategies to preempt third-party remanufacturers. The goal of our analytical model is to demonstrate the importance of incorporating the effect of remanufactured products on the perceived value of new products in determining an OEM's optimal strategy. In our model, we assume that the remanufactured products affect how consumers perceive new products and we allow for any magnitude of this effect. This enables our model to provide insights for different types of consumer products that may experience different magnitudes of this effect.

We first specify the discrete-time, infinite-horizon, dynamic game and then outline our assumptions regarding the product, firm, and market characteristics. We focus on a profit-maximizing firm (hereafter referred to as the OEM) that manufactures new products and may also choose to remanufacture its used products. The OEM may face competition from a profit-maximizing third-party remanufacturer, who can remanufacture used products originally produced by the OEM.

**Notation.** In the remainder of the essay, vectors are arranged in rows and primes represent transposes.  $\mathbf{1}$  denotes a vector of ones.  $\rho$  denotes the common discount factor of all players. Superscripts are used to label time (indexed by  $t \geq 0$ ) and subscripts  $o$ ,  $3p$  and  $c$  are used to denote OEM, third-party remanufacturer, and

consumer-specific parameters. In addition, subscripts  $n$  and  $r$  denote parameters associated with new and remanufactured products, respectively.

**Specification of the Game.** We develop a non-cooperative, discrete-time, infinite-horizon game, where all information is common knowledge. The OEM and the third-party remanufacturer (if present) move simultaneously in every period and announce prices of new and/or remanufactured products and then the consumers make their purchase decisions. Every period represents a period of use by the consumer, after which the product can be remanufactured for reuse. Thus, the product's useful life (without remanufacturing) is one period.

In order to focus on incorporating the effect of remanufactured products on the perceived value of the new products in determining an OEM's optimal decisions, we make the following two assumptions: First, similar to the existing literature, all products can be recovered, but remanufactured only once (Majumder and Groenevelt, 2001; Debo et al., 2005; Ferguson and Toktay, 2006; Ferrer and Swaminathan, 2006; Atasu et al., 2008b). This assumption allows us to account for the supply constraints in a simple and tractable manner (see Geyer et al., 2007 for further discussion). Second, collected cores cannot be inventoried and can only be sold in the next period. Thus, in every period, the quantity of remanufactured products that can be sold is constrained by the supply of cores, which is equal to the quantity of new products sold in the previous period. The first period begins without a supply of remanufacturable cores and there is an initial transient period where their supply builds up. In this infinite-horizon setting, we restrict our attention to steady-state equilibria. This assumption is common in several papers in the remanufacturing and durable goods literature (Hendel and Lizzeri, 1999b; Huang et al., 2001; Ferrer and Swaminathan, 2006).

**Cost Structures.** The OEM has a constant returns to scale production technology with the marginal cost of producing a new product denoted by  $c$ . The OEM and



the third-party remanufacturer have constant returns to scale collection and remanufacturing technologies, where the marginal costs are given by  $h_o$  and  $h_{3p}$ , respectively. Since remanufacturing is typically cheaper than new production, we assume  $0 \leq h_o, h_{3p} \leq c$ . Finally, we assume that there are no fixed costs associated with remanufacturing (see discussion in the appendix §A2).

**Consumer and Market Characteristics.** The consumer population remains constant over time and without loss of generality, we normalize its size to 1. We assume that consumers are heterogeneous and characterized by their type  $\theta$ , which represents their willingness-to-pay for a new product in the absence of a remanufactured product.  $\theta$  is uniformly distributed on  $[0, 1]$ .

Based on our experimental results, we assume that the consumer willingness to pay, denoted by  $u_i(\theta, j)$ , depends on the consumer's type  $\theta$ , whether the product is new or remanufactured ( $i = \{n, r\}$ ) and the identity of the firm(s) selling remanufactured products ( $j = \{o, 3p, b\}$ ); where  $j = o$  and  $j = 3p$  and  $j = b$  represent remanufactured products are sold by only the OEM, only the third party and both the OEM and the third party, respectively. Consumer  $\theta$  is characterized by the willingness-to-pay vector  $u(\theta, j) \doteq (u_n(\theta, j), u_r(\theta, j), 0)$ , which is time independent. Zero represents the value from remaining inactive,  $u_n(\theta, j) < \infty$  is the willingness to pay for a new product and  $u_r(\theta, j) < \infty$  is the willingness to pay for a remanufactured product.

In order to incorporate the effect of remanufactured products on the perceived value of new products, we only assume that the presence of the OEM's remanufactured products has a negative effect on the perceived value of new products and the presence of third party's remanufactured products has a positive effect on the perceived value of new products. We do not make any assumptions regarding the magnitude of the change in the perceived value of new products.

*Specification of the Consumer Model.* For the rest of the study, we assume the following functional forms for a consumer  $\theta$ 's willingness to pay:  $u_n(\theta, x) = \theta$ ,  $u_n(\theta, o) = \beta\theta$ ,  $u_n(\theta, 3p) = \alpha\theta$ ,  $u_r(\theta, o) = \phi_o\theta$  and  $u_r(\theta, 3p) = \phi_{3p}\theta$ , where  $0 < \phi_o < \beta \leq 1 \leq \alpha \leq 2$  and  $0 \leq \phi_{3p} \leq 1$ .

In this consumer model,  $\beta \leq 1$  denotes the reduction in the perceived value of the new product due to the presence of the OEM-remanufactured products, while  $\alpha \geq 1$  denotes the increase in the perceived value of the new product due to the presence of remanufactured products sold by a third-party remanufacturer.  $\phi_o$  ( $\phi_{3p}$ ) denotes the ratio of perceived value of the OEM's (third party's) remanufactured product,  $u_r(\theta, j)$ , and the perceived value of the new product in the absence of the remanufactured product,  $u_n(\theta, x)$ . As  $\phi_o$  or  $\phi_{3p}$  increase, the perceived value of the remanufactured product increases. As an example, the estimates for these parameters based on our experiment are  $\alpha = 1.32$ ,  $\beta = 0.85$ ,  $\phi_o = 0.64$ ,  $\phi_{3p} = 0.88$ . The willingness to pay for a remanufactured product relative to a new product, when the OEM remanufactures is  $\delta_o = \phi_o/\beta = 0.77$  and when the third party remanufactures is  $\delta_{3p} = \phi_{3p}/\alpha = 0.66$ . The standard consumer model used in the literature (e.g., Ferguson and Toktay, 2006; Ferrer and Swaminathan, 2006) is a special case (where  $\alpha = \beta = 1$ , and  $\delta_{3p} = \delta_o$  or  $1 = \delta_o \geq \delta_{3p}$ ) of our consumer model.

Under this consumer model, we assume  $c \leq \beta$ ,  $h_o \leq \phi_o$  and  $h_{3p} \leq \phi_{3p}$  to rule out uninteresting cases where no consumer purchases a product.

### **3.4 Analysis**

In this section, we first characterize a consumer's optimal strategies for a set of given prices for new and remanufactured products in §3.4.1. Based on this, we next characterize the OEM's decisions. Recall that our experiment suggests that when the OEM sells remanufactured products, the perceived value of new products may decrease, which has a negative impact on the profitability of the OEM. Thus, in §3.4.2, we

investigate an OEM's optimal remanufacturing strategy in the absence of remanufacturing competition and identify conditions when an OEM should pursue remanufacturing. Our experiment also suggests that when the third party sells remanufactured products, consumers may have a higher perceived value for the OEM's new products, which can enable the OEM to charge higher prices for its new products. However, the third party's remanufactured products still cannibalize the OEM's new product sales. So, could an OEM benefit from third-party competition? We provide insights for this question in §3.4.3. Building on the analysis in §3.4.2 and in §3.4.3, we characterize the OEM's optimal competitive strategy against a third-party remanufacturer in §3.4.4. In particular, we investigate if the presence of remanufacturing competition can be beneficial, under which conditions should an OEM allow the third party to remanufacture its used products? When is it better to remanufacture or collect cores to preempt third-party remanufacturers?

### 3.4.1 Characterizing Consumers' Optimal Decisions

We now focus on consumer decisions at any period  $t$ , for a given vector of prices  $p^t \doteq (p_n^t, p_r^t)$ , where  $p_n^t$  is the price of a new product and  $p_r^t$  is the price of a remanufactured product when the remanufactured products are either sold by the OEM or the third-party remanufacturer (see §3.5 for a discussion of the situation when the OEM and the third party both sell remanufactured products). Recall that we are considering an infinite-horizon game with discrete periods, where a product's useful life is one period. We define consumer  $\theta$ 's period- $t$  action vector as  $a^t(\theta) \doteq (b_n^t(\theta), b_r^t(\theta), i^t(\theta))$ , where  $b_n^t(\theta)$ ,  $b_r^t(\theta)$  and  $i^t(\theta)$  are indicator variables corresponding to buying a new product, a remanufactured product or remaining inactive. Since remaining inactive is included in the consumer's action set and each consumer has to make a decision in each period  $t$ , we have  $a^t(\theta)\mathbf{1}' = 1 \forall t, \theta \in [0, 1]$ . The useful life of a product is only one period, and consumers enter each period without a product. Thus, each consumer's

action in the current period depends only on the payoff in the current period, which is independent of the consumers' previous actions but depends on the OEM and the third-party remanufacturer's period- $t$  decisions. Consumer  $\theta$ 's optimal period- $t$  decision  $a^t(\theta)^*$  is determined by maximizing his period- $t$  net payoff  $\Pi_\theta[a^t(\theta); p^t, j]$  subject to  $a^t(\theta)\mathbf{1}' = 1$ , where  $\Pi_\theta[(1, 0, 0); p^t, j] = u_n(\theta, j) - p_n^t$ ,  $\Pi_\theta[(0, 1, 0); p^t, j] = u_r(\theta, j) - p_r^t$ , and  $\Pi_\theta[(0, 0, 1); p^t, j] = 0$ .

**Lemma 1** *In period  $t$ , the equilibrium consumer strategies have the following structure: In the absence of remanufactured products, only consumers in  $\theta \in (\theta_1, 1]$  buy a new product, where  $\theta_1 \in [0, 1]$  such that  $u_n(\theta_1, x) - p_n^t = 0$  and the demand for new products is given by  $q_n^t(p_n^t) = 1 - \theta_1$ . In the presence of remanufactured products ( $j = o$  or  $j = 3p$ ), consumers in  $\theta \in (\Theta_1, 1]$  always buy a new product, consumers in  $\theta \in (\Theta_2, \Theta_1]$  always buy a remanufactured product and consumers in  $\theta \in [0, \Theta_2]$  always remain inactive, where  $\Theta_2 \leq \Theta_1 \in [0, 1]$  such that  $u_r(\Theta_2, j) - p_r^t = 0$ ,  $u_n(\Theta_1, j) - p_n^t = u_r(\Theta_1, j) - p_r^t$ , and the demand for new and remanufactured products is given by  $q_n^t(p_n^t, p_r^t) = 1 - \Theta_1$  and  $q_r^t(p_n^t, p_r^t) = \Theta_1 - \Theta_2$ , respectively.*

Although a consumer's strategy is independent across periods, it is important to note that this is not true for an OEM's (or a third-party remanufacturer's) decisions. Since the quantity of remanufactured products that can be sold is constrained by the quantity of new products sold in the previous period, the OEM's decisions in period  $t$  depend on the decisions made in the previous period.

### 3.4.2 Should an OEM Remanufacture in the Absence of Competition?

Consider an OEM that does not face competition from a third-party remanufacturer. Recall that in our experiment, the presence of the OEM's remanufactured products was associated with a reduction in the perceived value of its new products (see Result 3 in §3.2.3). However, remanufacturing may also be beneficial due to the additional revenues and cost savings generated from selling remanufactured products. In this

section, we characterize the condition under which the benefits from remanufacturing outweigh the negative effect on the new products and it is profitable for an OEM to pursue remanufacturing.

Let  $\bar{p}_n^t$  and  $\bar{p}_r^t$  denote the price of new and remanufactured products sold by the OEM and let  $\bar{p}^t \doteq (\bar{p}_n^t, \bar{p}_r^t)$ . The OEM's per-period profit depends on the current and previous period decisions:  $\bar{\Pi}_o(\bar{p}^{t-1}, \bar{p}^t) \doteq (\bar{p}_n^t - c)\bar{q}_n^t(\bar{p}_n^t, \bar{p}_r^t) + (\bar{p}_r^t - h_o)\bar{q}_r^t(\bar{p}_n^t, \bar{p}_r^t)$ . In each period  $t$ , we need  $0 \leq \bar{q}_r^t(\bar{p}_n^t, \bar{p}_r^t) \leq \bar{q}_n^{t-1}(\bar{p}_n^{t-1}, \bar{p}_r^{t-1}) \forall t \geq 0$ , which captures the supply constraint on cores for remanufacturing products and the non-negativity constraints.

**Proposition 1** *In the absence of third-party competition, remanufacturing is profitable only if  $h_o \leq \bar{h}(\beta, \phi_o, c) \doteq \beta - c + \phi_o - (1 - c)\sqrt{\beta + 3\phi_o}$ .  $\bar{h}(\beta, \phi_o, c)$  is increasing in  $\beta$ ,  $\phi_o$  and  $c$ .*

According to Proposition 1, the OEM does not remanufacture if  $h_o > \bar{h}(\beta, \phi_o, c)$ , i.e., when the cost of remanufacturing is sufficiently high. In this case, the OEM only sells new products and the problem has a simple solution: The decisions in any period  $t$  do not depend on the previous period, all the periods decouple, and there is a unique and steady-state policy given by  $\bar{p}_n^* = \frac{1+c}{2}$ , and  $\bar{q}_n^* = \frac{1-c}{2}$ . The OEM's per-period profit is given by  $\bar{\Pi}_o^X = \frac{(1-c)^2}{4}$ .

However, when the remanufacturing cost is sufficiently low, i.e.,  $h_o \leq \bar{h}(\beta, \phi_o, c)$ , remanufacturing is profitable. The condition in Proposition 1 ensures that the cost savings from remanufacturing and the benefits due to market segmentation outweigh the cannibalization and the reduction in the perceived value of new products. A higher  $\beta$  implies a smaller reduction in the perceived value of new products, a higher  $c$  is associated with greater cost savings and a higher  $\phi_o$  is associated with a higher margin from remanufactured products. Thus, for higher values of  $\beta$ ,  $c$  or  $\phi_o$ , remanufacturing is profitable for higher values of the remanufacturing cost  $h$ .

The above result highlights the effect of remanufactured products on the perceived value of new products which has been ignored in the existing literature. It is not enough to just consider the trade-off between the benefits from remanufacturing and cannibalization of new products. OEMs also need to consider the potential negative impact of remanufactured products on the perceived value of new products. *Ignoring the effect of remanufactured products on the perceived value of new products might lead an OEM to remanufacture when it is not profitable to do so.*

This result has important managerial implications. If an OEM finds it profitable to pursue remanufacturing, it should attempt to moderate the negative effect of remanufactured products on new products. For example, consumer concerns may be alleviated by decoupling the sales of new and remanufactured products by selling new and remanufactured products through separate channels. This is in support for Apple's strategy of only selling remanufactured products on the internet, Electrolux's strategy of using different sales force and channels for selling remanufactured products and HP's strategy in Europe of selling remanufactured computers only through exclusive, secondary channels (Guide et al., 2005).

### **3.4.3 Can an OEM Benefit from a Third Party Remanufacturing its Products?**

We now focus on the OEM's decisions in the presence of competition from a third-party remanufacturer. In this setting, our model is a infinite-horizon,  $\rho$ -discounted, simultaneous, dynamic game with observable actions, which we know may have multiple equilibria from the Folk Theorem (Fudenberg and Tirole, 1991). As in the previous literature, we restrict our attention to pure-strategy Markov Perfect equilibria, which assumes that strategies only depend on the payoff-relevant history that is summarized by the current state (Fudenberg and Tirole, 1991).

Let  $p_n^t$  denote the price charged by the OEM for a new product. In this section, we assume that only the third-party remanufacturer sells remanufactured products.

Let  $p_r^t$  denote the price charged by the third party for a remanufactured product and  $p^t \doteq (p_n^t, p_r^t)$ . The per-period profit of both the OEM and the third party depend on the current and previous period decisions:  $\Pi_o^t(p^{t-1}, p^t) \doteq (p_n^t - c)q_n^t(p_n^t, p_r^t)$  and  $\Pi_{3p}^t(p^{t-1}, p^t) \doteq (p_r^t - h_{3p})q_r^t(p_n^t, p_r^t)$ . In each period  $t$ , we need  $q_n^t(p_n^t, p_r^t) \geq 0$  and  $0 \leq q_r^t(p_n^t, p_r^t) \leq q_n^{t-1}(p_n^{t-1}, p_r^{t-1})$  which represent the non-negativity constraints and the supply constraint on cores for remanufactured products.

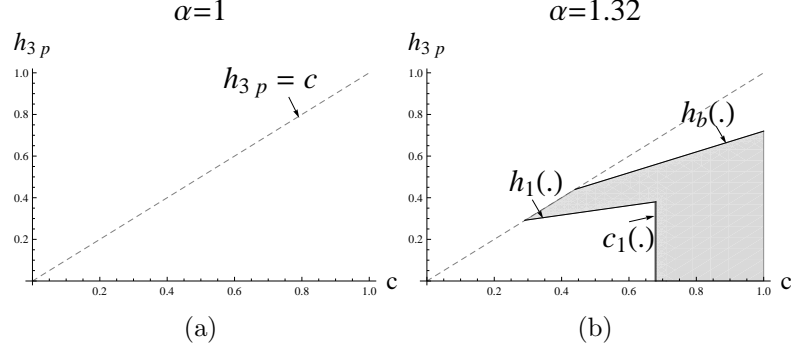
**Proposition 2** *In the presence of third-party competition, there exists  $h_b(\alpha, \phi_{3p}, c)$ , such that if  $h_{3p} < h_b(\alpha, \phi_{3p}, c)$ , then the third-party remanufacturer finds it profitable to compete with the OEM.*

Proposition 2 shows that the third-party remanufacturer will choose to enter the market only if i.e.,  $h_{3p} < h_b(\alpha, \phi_{3p}, c)$ . If the third party's remanufacturing cost is high enough,  $h_{3p} \geq h_b(\alpha, \phi_{3p}, c)$ , the competition from the OEM's new product is sufficient to deter the third party from remanufacturing products. Otherwise, the remanufacturing cost is low enough for the third-party remanufacturer to charge low enough prices to compete with the OEM and still remain profitable.

We next analyze the effect of third-party competition on the OEM's profitability. Proposition 3 shows that the presence of remanufacturing competition may not be detrimental for the OEM.

**Proposition 3** *Assume that  $h_{3p} < h_b(\alpha, \phi_{3p}, c)$  such that the third-party remanufacturer finds it profitable to remanufacture: there exists  $h_1(\alpha, \phi_{3p}, c)$  and  $c_1(\alpha, \phi_{3p})$  such that if  $h_{3p} > h_1(\alpha, \phi_{3p}, c)$  or  $c > c_1(\alpha, \phi_{3p})$ , then the OEM's profit is higher in the presence of remanufacturing competition.  $h_1(\alpha, \phi_{3p}, c)$  and  $c_1(\alpha, \phi_{3p})$  are increasing in  $\phi_{3p}$  but decreasing in  $\alpha$ .*

Proposition 3 shows that if the third party has a high remanufacturing cost but not high enough to deter entry or if the OEM has a high cost of new production, the



**Figure 5:** OEM profitability in the presence of remanufacturing competition ( $h < h_b(\alpha, \phi_{3p}, c)$ ) as a function of remanufacturing cost  $h$  and production cost  $c$  with  $\phi_{3p} = 0.88$ . The gray region is where OEM profitability is higher in the presence of remanufacturing competition. For illustrative purposes,  $\alpha = 1$  represents the assumption in the existing literature where there is no effect of the remanufactured products on the perceived value of new products and  $\alpha = 1.32$  is based on our experimental estimates.

presence of remanufacturing competition is beneficial for an OEM. The reason for this is as follows: Although the presence of the third-party remanufacturer leads to competition for an OEM, it may also increase the perceived value of the OEM's new products. If the third party has a high remanufacturing cost, it is less competitive and the negative effect of competition is outweighed by the benefits from an increase in the perceived value of new products. Similarly, if the OEM has a high cost of new production, it is less competitive and the benefits from an increase in perceived value of new products outweigh the negative impact of competition from a third-party remanufacturer.

The result in Proposition 3 is in contrast with the remanufacturing literature that shows the competition is detrimental for an OEM. For illustration, consider Figure 5a, where the perceived value of new products does not change in the presence of remanufactured products, i.e.  $\alpha = 1$  (as in the standard consumer model used in the existing literature). In this case, the only effect of the presence of the third-party remanufacturer is to force the OEM to lower its prices. However, if there is an increase in the perceived value of the new product ( $\alpha \geq 1$ ) in the presence of the third-party's



remanufactured product (see Figure 5b), the benefits from being able to charge a higher price for new products compensate for the negative effect of competition and the OEM finds the presence of the third-party remanufacturer beneficial.

These results have important managerial implications. *Competition from a third-party remanufacturer may be beneficial for OEMs. In addition, OEMs may still benefit from differentiating their new products from the remanufactured products sold by the third-party.* Similar approaches are also observed in practice. For example, HP does not actively preempt third-party competition, but rather tries to increase the perceived difference between their new printer cartridges and the third-party's remanufactured printer cartridges by using marketing techniques to reinforce that new cartridges are far superior than the remanufactured cartridges which have low quality and reliability (Hewlett-Packard, 2007; Hewlett-Packard, 2009).

#### **3.4.4 OEM's Optimal Strategy against Remanufacturing Competition: Preemptively Remanufacture, Preemptively Collect or Allow Third-Party to Remanufacture?**

Recall from the discussion in Proposition 2 that if the remanufacturing cost is sufficiently high,  $h_{3p} \geq h_b(\alpha, \phi_{3p}, c)$ , the third-party remanufacturer does not find it profitable to remanufacture products originally sold by the OEM. However, if the third party's remanufacturing cost is lower,  $h_{3p} < h_b(\alpha, \phi_{3p}, c)$ , the third party competes by remanufacturing products originally sold by the OEM and the presence of such remanufactured products may also increase the perceived value of the OEM's new products. Thus, in the presence of such remanufacturing competition, the OEM has to decide whether it should remanufacture its own products or let the third party to do so. In this section, we build on the results in §3.4.2 and §3.4.3, and characterize an OEM's optimal competitive strategy against a third-party remanufacturer.

Based on the strategies observed in practice and discussed in literature, we consider the following OEM strategies: preemptive remanufacturing, allowing the third

party to remanufacture its products or preemptive collection. Each one of these strategies has potential advantages and drawbacks, and the optimal competitive strategy depends on the comparison of the associated trade-offs.

**Preemptive Remanufacturing (R):** An OEM typically has the first-mover advantage in recovering used products for remanufacturing. This implies that if an OEM pursues remanufacturing, it will be more difficult for a third-party remanufacturer to recover cores. In order to model such a scenario, we assume that if the OEM pursues remanufacturing, the third-party remanufacturer is completely preempted and does not enter the market (see §3.5 for a discussion of the situation when remanufactured products are sold by both the OEM and the third-party remanufacturer). Note that this strategy can be beneficial due to the preemption of third-party competition and due to the cost savings and market segmentation. However, remanufacturing may also lead to the cannibalization of new product sales and a reduction in the perceived value of the new products (see Proposition 1).

**Allowing third-party competition (3P):** If an OEM does not pursue remanufacturing, a third party may remanufacture its products. Under such a strategy, the OEM forgoes the benefits from remanufacturing and faces competition from the third party's remanufactured products, but also enjoys an increase in the perceived value of its new products (see Proposition 3).

**Preemptive Collection (PC):** An OEM can also use a preemptive collection strategy, where it collects and disposes remanufacturable cores to preempt third-party remanufacturers (Ferguson and Toktay, 2006). We model this strategy in a simple manner, by assuming that under such a strategy, the OEM incurs an additional unit cost  $s$ , such that  $0 \leq s \leq c$  and the third-party remanufacturer is preempted. We also assume that there is no fixed cost of collection (see §A2 for a discussion). Thus, under this strategy, the OEM's problem is similar to the no-remanufacturing case discussed in §3.4.2, but with an effective cost of  $c + s$  for each new product sold. The

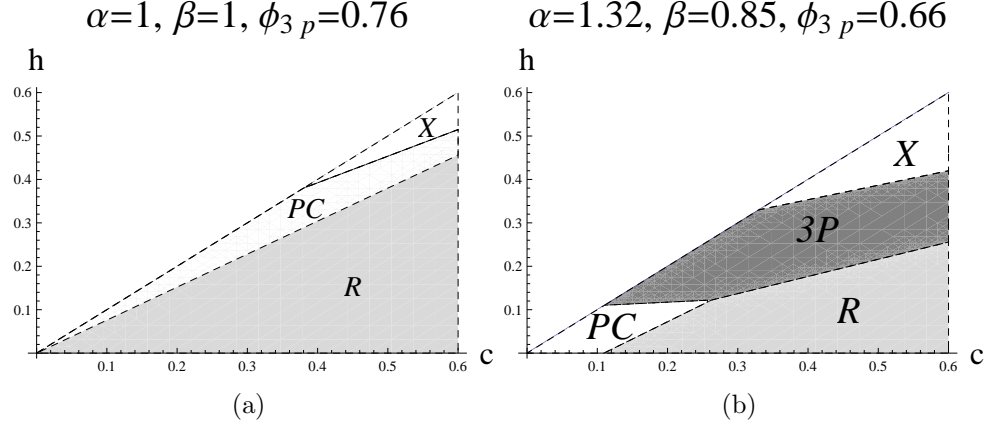
OEM's per-period profit in this case is given by  $\Pi_o^{PC} = (1 - c - s)^2/4$ . Note that although we specifically refer to this strategy as a preemptive collection strategy, it can be interpreted as any other preemptive strategy apart from OEM remanufacturing that prevents third-party remanufacturers from competing, e.g., designing products to prevent remanufacturing (similarly to Lexmark's preemption strategy, PC World, 2003). Although the OEM can benefit from preventing competition, this strategy can be costly and forgoes a potential increase in the perceived value of new products or the potential benefits from remanufacturing.

We now compare these strategies to determine the OEM's optimal strategy, which is summarized in the next proposition.

**Proposition 4** *Consider the situation when the third-party remanufacturer finds it profitable to enter the market,  $h_{3p} < h_b(\alpha, \phi_{3p}, c)$ . There exist  $h^-(\alpha, \beta, \phi_o, \phi_{3p}, c, h_{3p}, s)$ ,  $h^+(\alpha, \phi_{3p}, c, s)$  and  $c^-(\alpha, \phi_{3p}, s)$  such that the OEM's optimal competitive strategy against a third-party remanufacturer can be summarized as follows:*

1. *If  $h_o \leq h^-(\cdot)$ , the OEM should pursue preemptive remanufacturing (R).*
2. *If  $h_o > h^-(\cdot)$ , the optimal strategy depends on  $c$  and  $h_{3p}$ : If  $c \leq c^-(\cdot)$  and  $h_{3p} \leq h^+(\cdot)$ , the OEM should pursue preemptive collection (PC). Otherwise, the OEM should let the third party remanufacture its products (3P).*

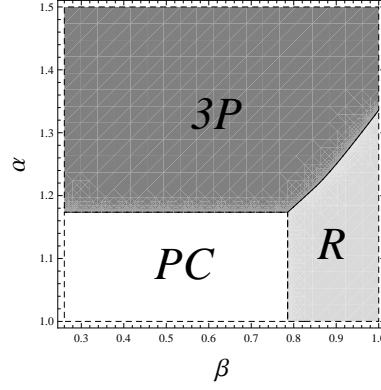
Proposition 4 characterizes the OEM's optimal competitive strategy against a third-party remanufacturer. Figure 6 illustrates this result and shows the importance of considering the effect of remanufacturing on the perceived value of new products in determining the optimal remanufacturing and competitive strategy. A comparison of panel (a) which is based on the standard consumer model used in the existing literature and panel (b) which is based on our consumer model leads to the following insight: *Ignoring the effect of remanufacturing on the perceived value of new products may lead an OEM to remanufacture its own products or collect cores to preempt competition, even to its own detriment.*



**Figure 6:** Importance of incorporating the effect of remanufactured products on the perceived value of new products in determining the OEM's optimal competitive strategy against a third-party remanufacturer with  $\phi_o = 0.76$ ,  $h \doteq h_{3p} = h_o$  and  $s = 0$ . Panel (a) is based on the standard consumer model used in the existing literature ( $\alpha = \beta = 1$  and  $\phi_o = \phi_{3p}$ ). Panel (b) is based on our consumer model ( $\beta \leq 1 \leq \alpha$  and  $\phi_{3p} \neq \phi_o$ ) and the experimental estimates from Figure 4. PC, R, 3P and X denote that the OEM's optimal strategy is preemptive collection, preemptive remanufacturing, letting the third party remanufacture its products or do nothing, respectively.

It can be seen from the above proposition and Figure 6 that the OEM's optimal strategy depends not only on the OEM's cost of new production and remanufacturing, but also on the third party's remanufacturing cost. If the OEM has a low remanufacturing cost, the cost savings from remanufacturing and the benefits from preempting the third party outweigh the cannibalization and the negative impact of OEM-remanufactured products on the perceived value of the new products. Thus, the OEM should pursue preemptive remanufacturing in this setting (Region R).

If the OEM has a high remanufacturing cost, the cost savings from remanufacturing are not enough for preemptive remanufacturing to be profitable. Instead, the OEM has to decide to either allow the third party to remanufacture its products, which increases the perceived value of new products, or pursue preemptive collection. This decision is driven by the competitiveness of the third party and the OEM. Recall from the discussion of Proposition 3 that a low remanufacturing cost represents a more competitive third party. Since for a lower cost of new production, the OEM



**Figure 7:** OEM's optimal competitive strategy as a function of  $\beta$  (the reduction in perceived value of new products in the presence of the OEM's remanufactured products) and  $\alpha$  (the increase in the perceived value of new products in the presence of the third party's remanufactured products), with  $h_{3p} = h_o = 0.1$  and  $c = 0.15$ . PC, R, 3P and X denote that the OEM's optimal strategy is preemptive collection, preemptive remanufacturing, letting the third party remanufacture its products or do nothing, respectively.

enjoys greater pricing power, the value from an increase in the willingness to pay of new products is lower. Thus, if both the third party's remanufacturing cost and the OEM's cost of new production are low enough, the benefits from preemptive collection outweigh the benefits from an increase in the perceived value of the new products and the OEM should pursue preemptive collection (Region PC). Otherwise, the benefits from an increase in the perceived value of new products outweigh the negative effect of competition and an OEM should allow the third party to remanufacture its products (Region 3P).

The thresholds in Proposition 4 also depend on the preemptive collection cost  $s$ . As collection becomes more expensive, the profitability of preemptive collection decreases and the regions where the OEM should remanufacture or allow the third party to remanufacture (Regions R and 3P) increase at the expense of the region where it should pursue preemptive collection (Region PC).

Figure 7 offers a different perspective and provides insights on how the OEM's

optimal competitive strategy should vary with the magnitude of the effect of remanufactured products on the perceived value of new products. An OEM can conduct an investigation of this effect for their specific product i.e., estimate the values of  $\alpha$ ,  $\beta$ ,  $\phi_o$  and  $\phi_{3p}$  for their product and determine the optimal competitive strategy against a third-party remanufacturer. If the reduction in the perceived value of new products in the presence of OEM-remanufactured products is lower, i.e.,  $\beta$  is higher, the profitability of OEM remanufacturing (R) increases. If the increase in the perceived value of new products due to the presence of third party-remanufactured products  $\alpha$  is higher, the profitability of letting the third party remanufacture (3P) increases. Similarly, the effect of change in the perceived value of the remanufactured products is as follows: an increase in the perceived value of an OEM's (third party's) remanufactured products,  $\phi_o$  ( $\phi_{3p}$ ), increases the profitability of Strategy R (3P).

### ***3.5 Conclusions, Limitations and Directions for Future Research***

In this study, we investigate the effect of remanufactured products on the perceived value of new products and how this influences an OEM's optimal competitive strategy against a third-party remanufacturer. To this end, we conducted an experiment using Apple iPods as an example of consumer products. In our experiment, we found that the presence of remanufactured products and the identity of the remanufacturing firm had a significant impact on the perceived value of new products. In particular, our experiment suggested that the presence of OEM-remanufactured products may have a negative impact on the perceived value of new products. This implies that the effect of remanufactured products on the perceived value of new products may reduce the profitability of remanufacturing for an OEM. However, an OEM can attempt to increase the profitability of remanufacturing by moderating the negative effect of remanufactured products. This could be achieved by targeting different markets and selling remanufactured products through separate or exclusive channels.

Interestingly, the presence of the third party's remanufactured products increased the perceived value of the OEM's new products in our experiment. This implies that an OEM may actually benefit from letting a third party remanufacture its products. Since the entry of remanufacturing competition may be beneficial, an OEM may even have an incentive to lower remanufacturing costs to encourage the entry of such competitors. However, an OEM may still benefit from other competitive strategies such as HP's strategy of informing customers about the relative higher performance of their new printer cartridges and trying to point out quality and reliability issues with the third party's remanufactured cartridges. While there might be other reasons for why an OEM may prefer to allow a third party to remanufacture its products and not pursue preemption (e.g., investment costs, lack of technology or strategic consumers in the context of relicensing fees in the IT industry, see Oraopoulos et al., 2007), our analysis offers a compelling consumer-side rationale for not preempting remanufacturing competition.

Based on these results, our analytical model shows that an OEM should carefully balance the effect of consumer perceptions of remanufactured products, cannibalization concerns and economics of remanufacturing to determine the optimal competitive strategy. Our key managerial insight is that an OEM should first investigate the effect of remanufactured products on the new products, before embarking on costly and potentially detrimental preemption. However, our results should be interpreted with caution. The main insight from our experiment is that there may exist a significant effect of remanufactured products on the perceived value of new products. However, the magnitude of this effect may vary for different products. Our experiment was carried out for one consumer product only, i.e., Apple iPods. However, the significance of our research lies in demonstrating the effect of remanufactured products and highlighting its impact on an OEM's competitive strategies. A natural direction for future research is to examine if the magnitude and the direction of the change in the

perceived value of new products generalize to other categories of consumer products and investigate the underlying mechanism causing this effect. Another future direction for research would be to investigate this effect in a business-to-business (B2B) setting, where decisions are typically based on procedures rather than individual perceptions. We conjecture that in this context, the effect of remanufactured products on new products may be moderated.

Finally, we made some assumptions in order to develop a parsimonious analytical model that nevertheless captures the key trade-offs associated with our research question. We assumed that remanufactured products are either sold by the OEM or the third-party remanufacturer and that when the OEM remanufactures, the third-party remanufacturer is completely preempted. These assumptions do not restrict the generality of our results and if relaxed, would significantly increase the complexity of the model, without offering any additional insights. In particular, if we extend our model, to consider exogenous core allocations (Majumder and Groenevelt, 2001), our main insights would still hold and there may be a region where the OEM will find it profitable to both pursue remanufacturing and let the third party remanufacture. Another important assumption in our model is that the OEM does not face competition from another OEM. Atasu et al. (2008b) has shown that OEMs can benefit from remanufacturing in the presence of low-end competitors. A interesting direction for future research would be to study the effect of remanufactured of products on the perceived value of new products in the presence of competition from other vertically-differentiated OEMs.



## CHAPTER IV

# TRADE-IN REBATES: PRODUCT RECOVERY AND PRICE DISCRIMINATION

### *4.1 Introduction*

It is well documented in the literature that many companies use trade-in rebates to entice customers to upgrade to a newer generation product (e.g., van Ackere and Reynolds 1995). In some settings (e.g., cars), the used product recovered from customers from a trade-in program has a residual value and can be re-sold again with little or no rework. In other settings, the used product may not be sold “as-is” without significant refurbishing, due to, perhaps, wearable parts (e.g., keyboard and batteries in computer laptops), or technological obsolescence (e.g., IT equipment with a second or third generation operating system). We consider the latter case and explore how the ability to practice price discrimination through trade-in rebates affects the OEM’s recovery and remanufacturing strategy. We begin by providing a short case study to illustrate this practice. While our case study is based on our observations from working with a particular company, we expect that similar practices are used at many other companies with a large installed base and whose primary sales strategy involves providing customized price quotes to each major customer.

#### **4.1.1 Short Case Study: Alpha**

Consider the case of Alpha<sup>1</sup>, a major OEM selling Internet hardware to mostly corporate customers. The majority of Alpha’s sales are handled by a sales team where each individual customer (typically a large business) is assigned a specific Alpha sales

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<sup>1</sup>The company’s actual name has been disguised.

agent. Because each sales agent is only responsible for a small number of accounts, s/he is able to develop an intimate knowledge of the customers' willingness-to-pay for Alpha products. This may be done in different ways; the sales agent may have a better understanding of the customer's business and/or their valuation during negotiations or through market research. Alpha must offer a public list price ( $p_n$ ) for its new products because some new customers will not have an assigned Alpha sales agent and may want to purchase an Alpha product through another channel such as Alpha's web site. Thus, an Alpha sales agent can never charge an existing customer a price above  $p_n$ , else the customer would just purchase the product through an alternate channel. Alpha commands a market share of over 75% for the majority of their product line, so near a monopoly market. Charging a single price of  $p_n$  means that Alpha loses profitable sales to all the customers with willingness-to-pay between the product's marginal cost and the list price  $p_n$ . Alpha would like to sell to these customers but does not want to lower the list price. Consider a product with a marginal cost of  $0.5p_n$  and a customer with a willingness-to-pay of  $0.8p_n$ . This customer does not buy the product at the list price but if the Alpha sales agent offers a customized private discount off the list price of 20% then the customer would buy the product and Alpha would make an additional profit of  $0.3p_n$ . Such blatant price discrimination is problematic, however, because other customers that pay the list price for Alpha products or receive lower discounts may hear about such discounts and demand similar treatment. For example, a famous example is the customer backlash in response to Amazon offering different prices to different customers on DVDs (J. Morneau, 2000). Thus, Alpha uses a mechanism where it can practice perfect price discrimination in a more subtle manner through their trade-in rebate program.

Alpha's historical sales data shows little correlation between the physical condition of the product traded in and the percentage discount off the list price awarded for the trade-in rebates. Because there is no published external valuation of used Alpha

products, customers accepting trade-in rebates have no way of knowing what the value of their used product is. Thus, they accept the estimate of the used product's value provided by the Alpha sales agent. Because Alpha does not remanufacture its returned products, it places zero value on the returned units, regardless of the model, condition, and age of the product. This allows the Alpha sales agent to offer the exact discount necessary for the customer to buy the product (perfect price discrimination), yet still be able to explain to the higher willingness-to-pay customers (who may hear about other customers receiving larger discounts) that the difference in the size of the discount is due to the characteristics of the used product that was traded in. This practice creates a much more opaque pricing scheme and completely disconnects the trade-in rebate discount from the true value of the unit being traded in. Some further evidence that Alpha uses its trade-in program to price discriminate is found by the fact that Alpha awards the discount with a simple oral promise: in over 50% of the sale transactions involving a trade-in in 2005, the customer did not bother returning the product to Alpha (Alpha leaves it up to the customer to return a used product to Alpha's centralized returns facility). Included in these cases were customers who received discounts of up to 20% off the list price for a new product. Finally, over 99% of all used products from trade-in rebates are scrapped at Alpha (at a possible cost), indicating that trade-ins, regardless of condition, do not have an immediate value to Alpha, and may actually incur a cost.

While the strategy described above has worked well for Alpha for many years, management is concerned that current and pending environmental legislation will make the disposal of returned units increasingly costly. Thus, there has been some discussion on whether Alpha should start remanufacturing its returned units (instead of recycling or disposal) and sell the remanufactured units at a discount off its new product's list price. Supporting reasons for this proposal are that some companies now consider remanufactured IT products as (imperfect) substitutes for new products, and

that there has been an increase in the number of remanufactured versions of Alpha's products being offered by third-party firms through outlets such as eBay Business. To date, however, the sales division of Alpha has argued strongly against offering remanufactured versions of Alpha's products, presumably because of their fear of losing the ability to perfectly price discriminate, in addition to the cannibalization threat. Remanufactured products have only been offered in a limited pilot program.

Inspired by Alpha's case study, we study in this essay the use of trade-in rebates to practice price discrimination by offering customized discounts in the presence of disposal costs for returned products, and a competing remanufactured product. Although there is literature indicating the use of personalized rebates—through negotiations—to achieve perfect price discrimination (e.g., Choudhary et al., 2005), we are the first, to our knowledge, to examine their effect on a firm's recovery and remanufacturing strategy. Typically, the firm needs to dispose the recovered units from the trade-in program, typically at a cost (e.g., materials recycling). We show that irrespective of the disposal cost, the OEM can price discriminate by offering such trade-in rebates and achieve higher profits. We extend the literature on price discrimination, personalized pricing and trade-ins by considering the possible presence of a remanufactured product as an imperfect competitor for the new product. We model both internal competition (when the OEM remanufactures the used units she recovers from the trade-in program) and external competition (when the remanufactured product is offered by a third-party entrant). We find that the monopolist is less likely to offer a remanufactured product (with the used products recovered from the trade-in program), because offering the remanufactured product diminishes the ability of the firm to practice price discrimination. Interestingly, however, the OEM is worse off if she allows instead the remanufactured product to be offered by a third-party remanufacturer. Thus, our results shed some light on the secondary market strategies of many firms that were previously not explained by the existing

literature.

The rest of the essay is organized as follows: In the next section, we position our research in the context of the relevant literature. Our key assumptions and notation are outlined in §4.3. In §4.4.1, we investigate the case where a monopolist can price discriminate by using trade-in rebates. In §4.4.2, the OEM decides to offer a remanufactured version of the (older generation) product to take advantage of the trade-ins. In §4.4.3, there is threat of entry by a third-party remanufacturer. We conduct a numerical study in §4.5 to study the impact of the remanufactured product on profit under various scenarios. In §4.6, we summarize our results and conclude with managerial implications. All proofs are provided in the Appendix.

## ***4.2 Literature Review***

Our research draws on several streams of literature: durable goods and trade-ins, price discrimination, as well as competition and cannibalization in remanufacturing. We provide a brief overview of each with the goal of positioning our work in relation to the previous literature.

For a review of durable goods theory in economics and its application to real world markets, see Waldman (2003). We focus here on the subset of the literature that investigates the role of trade-in rebates. The basic argument, as stated in, e.g., Van Ackere and Reyniers (1995), is that trade-in rebates offer an incentive for customers to replace an existing product with a new one quicker than they would otherwise without the rebate. The authors show that it is not optimal for the OEM to offer trade-in rebates for products that depreciate quickly (that is, quasi-consumable goods) because customers already have an incentive to replace their existing product frequently. Using a two-period model, Levinthal and Purohit (1989) show that trade-in rebates allow the firm to disable the second-hand market when it introduces a new and improved product generation. Rao et al. (2009) model heterogeneity in used products to argue that

trade-in rebates are a tool for the OEM to intervene in the second-hand market by decreasing the number of “strategic holders” (i.e., remove “lemons” from the market). Ray et al. (2005) also model heterogeneity in the used products’ condition (through an age distribution) and suggest an optimal age-dependent trade-in rebate, assuming the firm can derive revenues from the used product (possibly from remanufacturing), and that these revenues are decreasing in age. They consider remanufactured products as perfect substitutes and remanufacturing is cheaper than new production. Thus, they find that for a monopolist firm, recovering products through a trade-in rebate program and remarketing them is always profitable. In contrast, we show that it may be optimal for the firm to recover products through a trade-in program and scrap them. In addition, as our case study demonstrates, OEMs may face competition from (lower quality) remanufactured products (either internal or offered by a third-party), so our model incorporates this feature as well.

Cui et al. (2007) discuss how trade promotions can be used to price discriminate different retailers. Choudhary et al. (2005) study perfect price discrimination in a duopoly with vertical differentiation, where a firm can offer a personalized price based on complete knowledge of the willingness-to-pay of each consumer. In their setting, each firm chooses a quality level for their product and offer a personalized price to every consumer. In contrast, in our model quality is exogenous and there are new and remanufactured products, where the remanufactured products are perceived to be of lower quality than new products; this perception is outside of the firm’s control. Also, the firm’s decision variable is the list price, with perfect price discrimination occurring only for customers with willingness-to-pay below the list price and the firm has to dispose of the traded-in products.

Another stream of literature focuses on the competition (both internal and external) between new products and their remanufactured equivalents. Debo et al. (2005) study an OEM who considers selling both new and remanufactured products to a

customer base that demands a discount for the remanufactured product. They determine the OEM's optimal market segmentation and remanufacturability level decisions with and without third-party remanufacturers. Jin et al. (2007) extend this model by generalizing the relative consumer utility for remanufactured products. Majumder and Groenevelt (2001) model competition between an OEM and an entrant on the availability of used products. Ferrer and Swaminathan (2006) study the optimal pricing schemes for the OEM as well as for a third-party entrant in a multi-period setting when the customer values the entrant's product less. Ferguson and Toktay (2006) analyze two common entry-deterrent strategies an OEM may use to deter external competition: remanufacturing themselves and preemptive collection with disposal. They find that an OEM may choose to remanufacture or preemptively collect her used products to deter entry, even when she would not have chosen to do so under a pure monopoly environment. Atasu et al. (2008b) provide a model that explicitly incorporates specific demand-related issues, such as the existence of a green segment, competition, and product life cycle effects. Finally, Oraiopoulos et al. (2007) study an OEM's incentives to control the secondary market in the IT industry through the setting of relicensing fees. In their model, the future resale value of a used piece of IT equipment is implicitly included in the customer's original valuation of a new product. They find that this impact on new product sales is large enough that the OEM never eliminates the secondary market, even when it is within her means of doing so.

Similar to the papers mentioned above, we also model the competition (both internal and external) between new and remanufactured products and explore why an OEM may choose not to participate in the remanufactured product market. The unique aspect of our model, compared to the previous research stream, is that we explore an additional powerful reason that an OEM may choose not to offer remanufactured versions of her product. By doing so, her ability to practice *perfect* price

discrimination through trade-in rebates is limited, as some customers might derive greater utility from purchasing a remanufactured product instead of obtaining a new product through the trade-in rebate program. This leads to a greater loss of profits when the OEM is able to price discriminate by using such a program. This added incentive not to remanufacture (compared to the earlier cases where the ability to practice perfect price discrimination was not modeled) may explain why some firms do not remanufacture even though the previous models predict they should. We also show however, that this hesitation to remanufacture is mitigated when there is competition from a third-party entrant.

### ***4.3 Key Model Assumptions***

We consider an OEM who manufactures a product that undergoes some major re-design every few years due to advances in the technology. For example, Alpha's products have a four to six-year life-cycle. At the end of the product's life-cycle, customers can replace the product with a newer generation model (the new product), or with a remanufactured product (if available). The previous generation product has to be remanufactured to extend its useful lifetime by updating the main software and wearable parts, such that it is an imperfect substitute for the new product. Without loss of generality, the market size is normalized to one. Our major assumptions are as follows:

**Assumption 1** *Consumer willingness-to-pay is heterogeneous and uniformly distributed in the interval  $[0, 1]$ .*

We assume that the consumers' willingness-to-pay for the new product are distributed uniformly in the interval  $[0, 1]$  and that in any period, each consumer uses at most one unit. The market size is normalized to 1. In this model, a consumer of type  $\phi \in [0, 1]$  has a willingness-to-pay of  $\phi$  for a new product and her net utility from purchasing is  $\phi - p_n$ , where  $p_n$  is the price paid for the new product.



**Assumption 2** *There is a fraction  $\alpha \in [0, 1]$  of the potential customer base, independent of the customer's willingness-to-pay, who would not consider purchasing a remanufactured product.*

An alternative way to write this assumption is that, with probability  $\alpha$ , a customer would not consider purchasing a remanufactured product, regardless of its price. This assumption is based on the common observation that many customers demand top performance, and therefore prefer to have the latest technology. In consumer goods, we find evidence of this assumption in the high premiums paid by consumers for new gadgets such as the iPhone, which at a \$599 price tag (compared to other phones offered by AT&T at less than \$50), still attracts a significant number of buyers—270,000 buyers in the first few days of sales.<sup>2</sup> Based on our discussions with managers from Alpha, we believe the existence of such a segment is true, although perhaps to a less extent, in B2B markets. Our parameter  $\alpha$  allows us to model this phenomenon to any degree, including the most common case in the previous literature where all customers consider buying the remanufactured product if available ( $\alpha = 0$ ).

**Assumption 3** *For customers who consider purchasing a remanufactured product ( $1 - \alpha$ ), their willingness-to-pay for a remanufactured product is a fraction  $\delta$  of their willingness-to pay for the new product.*

Under this assumption, a consumer with a willingness-to-pay  $\phi$  for a new unit has a willingness-to-pay of  $\delta\phi$  for the remanufactured unit. Thus, the nature of competition between new and remanufactured products is that of vertical differentiation (consumers prefer a new product to a remanufactured one for the same price). There is considerable evidence that customers generally perceive remanufactured products to be of “lower quality” than new products, even if they belong to the *same* technological generation. This perspective is reflected in a number of articles in the practitioner

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<sup>2</sup><http://www.apple.com/pr/library/2007/07/25results.html>

and academic literature (Lund and Skeels, 1983; Hauser and Lund, 2003; Debo et al., 2005; Vorasayan and Ryan, 2006; Atasu et al., 2008b). In addition, an empirical study using online auctions by Guide and Li (2009) indicates that customers' willingness-to-pay for remanufactured routers is about 15% lower than for new routers, with both new and remanufactured routers from the same technological generation and carrying identical warranties from the OEM. Note that if  $\delta = 0$ , consumers are not willing to pay anything for the refurbished product; this eliminates the option of maintaining a secondary market. If  $\delta = 1$ , consumers view the new and refurbished units as being identical and are willing to pay the same amount for either product. Most products fall between the two extremes; we assume  $0 < \delta < 1$ .

**Assumption 4** *The OEM incurs a cost  $0 \leq s \leq c$  for every unit disposed.*

Depending on the nature of the materials that makes up a product, a firm may incur a positive fee for disposing of a used product. We assume that only the OEM incurs this cost. Thus, a customer that does not trade-in a used product can dispose of the product at zero cost. This assumption is reflective of the current regulatory environment and social expectations. Since the quantity disposed by individual consumers is small, landfill bans and fees typically do not apply or are lower. For example, in U.S. only non-household entities generating more than 220 lbs. of hazardous e-waste per month are regulated under the federal law (U.S. EPA, 2008b). Where regulations apply to neither consumers nor firms, firms may nevertheless recycle due to pressure from environmental groups to dispose the used product in an environmentally responsible manner and incur a cost that individual consumers do not. For example, there is considerable pressure by NGOS such as the Silicon Valley Toxics Coalition (<http://svtc.etoxics.org>) on IT producers, as opposed to users. Note that this assumption is equivalent to assuming consumers have a lower disposal cost than the OEM and is normalized to zero.

**Table 3:** Parameters and decision variables

Symbol	Definition
$c$	Unit production cost (new product)
$c_r$	Cost to remanufacture one product
$s$	OEM's unit disposal cost for the product traded in
$\phi$	Customer willingness-to-pay
$\alpha$	Fraction of market who only consider new products
$\delta$	Relative willingness-to-pay (remanufactured/new)
$p_{n2}$	Second-Period Unit (list) price for new product
$q_{n2}$	Second-Period Quantity of new products
$p_r$	Unit price for remanufactured product
$q_r$	Quantity of remanufactured products
$p_1$	First-Period Unit (list) price for new product

We assume that the OEM can produce new products at a per-unit cost of  $c$  such that  $0 \leq c < 1/3$ . Since, the maximum willingness-to-pay for a new product is 1, the unit cost must satisfy  $c < 1$  to ensure that the firm can profitably manufacture the new product in the first place. In order to simplify the exposition throughout the paper, we impose the constraint  $c < 1/3$  which does not change any insights (The results under  $1/3 \leq c$  can be found in the appendix). Finally, we consider a two-period model, which is common in the durable goods and closed-loop supply chain literature (see §4.2). The beginning of the first period can be thought of as the time a new generation of the product is introduced in the market place and the end of it is the time before the introduction of the following generation. The firm only produces new products in the first period, which are then available for remanufacturing in the second period (when there is the competition between new and remanufactured products). Thus, using a two-period model helps us to capture the key problem dynamics while still maintaining analytical tractability.

## 4.4 Analysis

### 4.4.1 Monopoly: Perfect Price Discrimination and No Remanufacturing

We begin with the well-established case where the OEM does not remanufacture and offers a single price for her product. With no trade-in program, the OEM's objective in both periods is given by

$$\max_{p_{ni}} \Pi_i^{NN} = (p_{ni} - c)(1 - p_{ni}), \quad i \in \{1, 2\}$$

which is concave in  $p_{ni}$  (the superscript "NN" denotes no price discrimination and no remanufacturing). First-order conditions yields the familiar monopoly results of

$$p_{ni}^{NN*} = \frac{1+c}{2}, \quad q_{ni}^{NN*} = \frac{1-c}{2}, \quad \Pi^{NN*} = \Pi_1^{NN*} + \Pi_2^{NN*} = \frac{(1-c)^2}{2}. \quad i \in \{1, 2\} \quad (8)$$

With this benchmark case in mind, we now show how the OEM can achieve a higher profit than  $\Pi^{NN*}$  by practicing price discrimination with trade-in rebates. We assume (in this section only) that there is no remanufactured product. This could occur due to many reasons: the OEM is diligent in destroying all used units it recoups; customers are not interested in remanufactured products (e.g., retreaded tires for passenger cars in the U.S.) implying  $\alpha = 1$ ; remanufacturing is not economical (e.g., old and obsolete computers), among other reasons. In the first period, the firm offers new products at a list price of  $p_1$  and the total quantity of products sold is  $q_1 = 1 - p_1$ . The firm offers new products in the second period at a list price of  $p_{n2}$  and customers with willingness-to-pay higher than  $p_{n2}$  will buy the product at the list price. The firm can offer a trade-in rebate which is a discount off the list price to customers who own a previous generation product and cannot afford to buy the new product at the list price. If the discounts are high enough, some of these customers will choose to return their older product and purchase a new product. This enables the firm to practice price discrimination in a subtle manner through the trade-in rebate program. The firm's optimal price for a new product in the second period should satisfy the condition summarized in the following lemma:

**Lemma 1** *The OEM should always charge a higher list price for the new product in the second period, i.e.  $p_1 \leq p_{n2}$ .*

The above lemma implies that the OEM should set the list price for the new product such that there is a segment of consumers who own a used product and cannot afford to purchase a new product at the list price. The OEM will price at each consumer's willingness-to-pay  $\phi$  (upto  $p_{n2}$ ), and will sell to every customer who satisfies the following two conditions: first, the consumer must own a product to be able to take advantage of the trade-in program (i.e.  $\phi \geq 1 - p_1$ ) and second, has a willingness-to-pay above her per-unit production cost  $c$  plus her per-unit disposal cost  $s$ . Thus, setting the optimal list price according to Lemma 1 ensures that the OEM will always be able to practice price discrimination in the second period. For consumers with willingness-to-pay  $\phi$  above  $p_{n2}$ , however, the OEM does not offer a trade-in credit because she cannot charge a higher price than the product's list price  $p_{n2}$ . Consequently, all customers with willingness-to-pay above  $p_{n2}$  are not offered the trade-in program, and as a result pay the list price  $p_{n2}$ . The total quantity of new products in the second period is  $q_{n2}^{MN} = (1 - p_{n2}) + (p_{n2} - k) = 1 - k$ , where  $k = \max(p_1, c + s)$ . The OEM's second-period objective is given by (where the superscript 'MN' means "monopoly, no remanufacturing"):

$$\begin{aligned} \max_{p_{n2}} \Pi_2^{MN}(p_1) &= (1 - p_{n2})(p_{n2} - c) + \int_k^{p_{n2}} (\phi - c - s) d\phi \\ \text{s.t.} \quad k &= \max(p_1, c + s) \end{aligned}$$

After characterizing the OEM's optimal second-period list price, we now solve for the optimal first-period list price decision. We maximize the total two-period profit  $\Pi^{MN}(p_1) = (1 - p_1)(p_1 - c) + \Pi_2^{MN*}(p_1)$  to determine  $p_1^{MN*}$  and  $\Pi^{MN*} \doteq \Pi^{MN}(p_1^{MN*})$ .

**Proposition 1** *If the OEM offers a trade-in rebate program for new products and does not offer a remanufactured version of the product, then the optimal list prices*

are given by  $p_1^{MN*} = \frac{1+2c+s}{3}$ ,  $p_{n2}^{MN*} = 1 - s$  and the total two-period profit is given by  $\Pi^{MN*} = \frac{(1-c)^2}{2} + \frac{(1-c-2s)^2}{6}$ .

Note that the total profit under this case is strictly higher than under no price discrimination, irrespective of the disposal cost, i.e. the OEM is never worse off offering a trade-in program when she can selectively offer trade-ins. The intuition for this is that the OEM has more price flexibility with the trade-in program. She reaches customers with willingness-to-pay too low to buy the product at list price, and since she never sells below total cost ( $c + s$ ), she is better off, no matter how high the disposal cost  $s$ . Thus, in a monopoly market with no competition from remanufactured products, the OEM is no worse off offering a trade-in rebate program even when disposal of traded in units is costly. This explains how and why the OEM uses price discrimination only on the set of customers who already own the OEM product. This practice however, leaves the OEM with a large quantity of used products for which the OEM must pay a fee to dispose. It is reasonable to ask if the OEM could be better off by remanufacturing and reselling the returned products rather than paying the potentially costly disposal fee. For example, Alpha has been studying this option due to the volume of returned products. We study this case in the next section.

#### **4.4.2 Perfect Price Discrimination in the Presence of a Remanufactured Product Offered by the OEM**

With the trade-in program, the OEM recovers a significant portion of used (older generation) products. We now consider that the OEM also offers a remanufactured version of the (older generation) product at a price  $p_r < p_{n2}$ . This induces some degree of cannibalization on the new product. Recall that, a fraction  $\alpha$  of all customers, distributed uniformly over the customer base, do not consider the remanufactured product as an option, as it belongs to an older technological generation. Thus, there

are  $1 - \alpha$  customers who consider buying a remanufactured product if the “price  $p_r$  is right”.

Consider a customer of valuation  $\phi$ . If  $\phi < p_{n2}$ , the customer obtains a negative utility from the new product, but a  $\delta p_r - \phi$  net utility from the remanufactured product, which is positive for  $\phi > \frac{p_r}{\delta}$ . On the other hand, if  $\phi > p_{n2}$ , both products have positive net utilities, and for high enough values of  $\phi$  (specifically, for  $\phi > \frac{p_{n2} - p_r}{1 - \delta}$ , found by solving  $\phi - p_{n2} > \delta\phi - p_r$ ), the net utility for the new product is higher than that of the remanufactured product. Summarizing, the  $1 - \alpha$  segment customers with valuation higher than  $\frac{p_{n2} - p_r}{1 - \delta}$  will buy a new product, those with valuation between  $\frac{p_r}{\delta}$  and  $\frac{p_{n2} - p_r}{1 - \delta}$  will buy the remanufactured product, and those with valuation less than  $\frac{p_r}{\delta}$  will not buy anything. The OEM can offer the trade-in rebate program to the small segment of consumers with valuations below  $\frac{p_r}{\delta}$  and who own a product to trade-in their older product and buy a remanufactured product. However, we assume that the OEM does not offer trade-in rebates to this segment for buying remanufactured products. Relaxing this assumption increases the analytical complexity of the model, without offering any additional insights. This assumption also reflects the current industrial practice where the sales force has stronger incentives to push new products to customers (as they typically command premium profit margins) and will prefer to focus on consumers considering new products for marketing the trade-in rebate program. The quantities of new products sold to the  $\alpha$  segment ( ${}^\alpha q_{n2}$ ), new and remanufactured products sold to the  $1 - \alpha$  segment ( ${}^{1-\alpha} q_{n2}$  &  $q_r$ ) are given by

$${}^\alpha q_{n2}(p_{n2}, p_r) = \alpha [(1 - p_{n2}) + (p_{n2} - k)] = \alpha(1 - k), \quad (9)$$

$${}^{1-\alpha} q_{n2}(p_{n2}, p_r) = (1 - \alpha) \left(1 - \frac{p_{n2} - p_r}{1 - \delta}\right) \quad (10)$$

$$q_r(p_{n2}, p_r) = (1 - \alpha) \frac{\delta p_{n2} - p_r}{\delta(1 - \delta)}. \quad (11)$$

The OEM’s second-period objective (where the superscript “MR” means “monopoly,

remanufacturing”) is given by:

$$\begin{aligned} \max_{p_{n2}, p_r} \Pi_2^{MR} = & \alpha \left[ (1 - p_{n2})(p_{n2} - c) + \int_k^{p_{n2}} (\phi - c - s) d\phi \right] \\ & + (1 - \alpha) \left[ \left( 1 - \frac{p_{n2} - p_r}{1 - \delta} \right) (p_{n2} - c) + \frac{(\delta p_{n2} - p_r)}{\delta(1 - \delta)} (p_r - c_r) + \int_{\frac{p_r}{\delta}}^{\frac{p_{n2} - p_r}{1 - \delta}} s d\phi \right] \end{aligned} \quad (12)$$

The terms in the left-hand side of (12) represent respectively: sales of new products to  $\alpha$  customers at list price, sales of new products to  $\alpha$  customers using the trade-in rebate program, sales of new products to  $1 - \alpha$  customers at list price, sales of remanufactured products and avoided disposal cost for products which were remanufactured and offered to consumers. In addition, there are constraints. The first constraint is that the number of new units sold to the  $1 - \alpha$  customers who also consider buying a remanufactured product should be non-negative. That implies, from (10),  $p_{n2} - p_r \leq 1 - \delta$ . (Clearly, the number of new units sold to the  $\alpha$  customers who do not consider buying a remanufactured product is non-negative, as seen from (9)). The second constraint is  $q_r \geq 0$ , which implies, from (11),  $\delta p_{n2} - p_r \geq 0$ . The number of remanufactured products offered, i.e.,  $(1 - \alpha) \frac{(\delta p_{n2} - p_r)}{\delta(1 - \delta)}$  is limited by the number of used units recovered by the OEM through the trade-in program, i.e.  $\hat{q}(p_{n2}, k) \doteq \alpha(p_{n2} - k)$ . Finally, trade-in rebates can be only offered to consumers in the segment  $\alpha$  who own a used product and have a willingness-to-pay higher than above the per-unit production cost  $c$  plus the per-unit disposal cost  $s$ . Thus, the firm solves the optimization problem comprised of the objective function (12) and the following constraints:

$$p_{n2} - p_r \leq 1 - \delta \quad (13)$$

$$\delta p_{n2} - p_r \geq 0 \quad (14)$$

$$(1 - \alpha) \frac{(\delta p_{n2} - p_r)}{\delta(1 - \delta)} \leq \alpha(p_{n2} - k) \quad (15)$$

$$k \doteq \max(p_1, c + s) \leq p_{n2} \quad (16)$$

Note that  $k \leq p_{n2}$  also implies that  $c + s < 1$  is always required to hold. After



characterizing the OEM's optimal second-period list price, we solve for the optimal first-period list price decision. We maximize the total two-period profit  $\Pi(p_1)^{MR} = (1 - p_1)(p_1 - c) + \Pi_2^{MR*}(p_1)$  to determine  $p_1^{MR*}$  and  $\Pi^{MR*} \doteq \Pi^{MR}(p_1^{MR*})$ . The OEM's optimal strategy is given by Proposition 2 below.

**Proposition 2** *If the monopolist markets a trade-in rebate program for new products along with a remanufactured version of the product, then the monopolist's optimal strategy is dependent on its per-unit production cost  $c$  relative to other parameters as follows:*

Condition 1 : If  $c \leq c_1$ , then the optimal prices are given by  $p_{n1}^{MR*} = \frac{1+\alpha s+c(1+\alpha)}{2+\alpha}$  and  $p_{n2}^{MR*} = \frac{1-\alpha s+c(1-\alpha)}{2-\alpha}$ . In this case, the monopolist does not market remanufactured products ( $q_r^{MR*} = 0$ ), and consumers in both segments buy the new product ( $q_{n2,1-\alpha}^{MR*} > 0, q_{n2,\alpha}^{MR*} > 0$ ).

Condition 2 : If  $c_1 < c < c_2$ , then the optimal prices are given by the table below. In this case, the monopolist sells remanufactured products ( $q_r^{MR*} > 0$ ), and consumers in both segments buy new products ( $q_{n2,1-\alpha}^{MR*} > 0$  and  $q_{n2,\alpha}^{MR*} > 0$ ).

Case	$p_{n1}^{MR*}$	$p_{n2}^{MR*}$	$p_r^{MR*}$
$c < \min(c_a, c_b)$	$\frac{1+\alpha s+c(1+\alpha)}{2+\alpha}$	$\frac{1-\alpha s+c(1-\alpha)}{2-\alpha}$	$\frac{(c_r-s)(2-\alpha)+2\delta(1-\alpha s)-\alpha\delta c}{2(2-\alpha)}$
$c_a \leq c < c_b$	$p_1^1$	$\frac{(1-\alpha)(c+s-c_r+2\delta p_1^1)+(1-\delta)(1-\alpha s)}{2-\alpha-\alpha\delta}$	$\frac{\delta((1-\alpha)(c+s-c_r+2\delta p_1^1)+(1-\delta)(1-\alpha s))}{2-\alpha-\alpha\delta}$
$c_b \leq c$	$p_1^2$	$p_{n2}^2$	$p_r^2$

Condition 3 : If  $c_2 \leq c$ , then the optimal prices are given by the table below. In this case, the monopolist sells remanufactured products ( $q_r^{MR*} > 0$ ), and the new product is only chosen by consumers in the  $\alpha$  segment ( $q_{n2,1-\alpha}^{MR*} = 0, q_{n2,\alpha}^{MR*} > 0$ ).

Case	$p_{n1}^{MR*}$	$p_{n2}^{MR*}$	$p_r^{MR*}$
$c < \min(c_c, c_d)$	$\frac{1+\alpha s+c(1+\alpha)}{2+\alpha}$	$\frac{(1-\alpha)(c_r-s+\delta)+\alpha\delta(\delta-s)}{2-2\alpha+\alpha\delta}$	$\frac{(1-\alpha)(2+c_r-s)-\delta(1-2\alpha+\alpha s)}{2-2\alpha+\alpha\delta}$
$c_c \leq c < c_d$	$p_1^3$	$1 - \delta + \delta p_1^3$	$\delta p_1^3$
$c_d \leq c$	$p_1^4$	$\frac{1-\alpha+\alpha\delta p_1^4}{1-\alpha+\alpha\delta}$	$\frac{\delta(1-2\alpha+\alpha p_1^4+\alpha\delta)}{1-\alpha+\alpha\delta}$

The optimal solution in Proposition 2 can be described as follows: If  $c \leq c_1$ ,

the new product's manufacturing cost is low enough (relative to the remanufacturing cost) that it is optimal for the OEM to only produce the new product. If  $c_1 < c < \min(c_a, c_b)$ , the OEM should remanufacture a small fraction of the recovered products, however, she should still set the list price for the new products in a similar manner as under no remanufactured products. Under both of the conditions discussed above, simple algebra yields  $p_{n2}^{MR*} \leq p_{n2}^{MN*}$  &  $p_1^{MR*} \leq p_1^{MN*}$  which hold with equality if  $\alpha = 1$ . Thus, relative to the MN case where there is price discrimination without remanufactured products, the OEM has to lower the list prices for the new products, when it markets remanufactured products. Thus, the OEM should charge a lower list price for the new product and market them to both segments.

If  $c_a \leq c < c_b$ , the per-unit production cost is higher (as compared to the remanufacturing cost) and since remanufacturing becomes more attractive, the firm should remanufacture a higher fraction of the products recovered from trade-ins. In addition, the OEM should charge a different list price for new products compared to the two cases discussed above. Thus, the OEM still finds it profitable to pay the fee for disposal of the remaining recovered products, which were not remanufactured. If the production cost is higher i.e.  $c_b \leq c < c_2$ , the optimal quantity of remanufactured products is constrained by the availability of older units recovered from the trade-ins and she remanufactures all of the units recovered from the trade-in program.

If the production cost is lies between  $c_2$  and  $c_d$ , the high list price for the new product prevents the customers in the  $1 - \alpha$  segment to purchase a new product and they only buy remanufactured products. The higher list price for the new product enables the firm to market trade-in rebates to a larger segment of consumers and practice price discrimination. However, the OEM should only remanufacture a fraction of the recovered products and pay for the disposal of the remaining units. If the cost to produce a new product is extremely high  $c_d \leq c$ , it is more profitable to remanufacture all of the available units. Thus, under this setting ( $c_2 \leq c$ ) the

firm should market new products to the  $\alpha$  segment, charge a high list price and price discriminate by marketing trade-in discounts to the rest.

Recall that if  $c < \min(c_a, c_b)$ , the OEM has to charge lower list price for the new products. As a result profits decrease, as shown by our numerical study over realistic range of parameters, later in §4.5, where we find that profits decrease in 81.69% of the scenarios and it is not optimal for the OEM to market remanufactured products under those scenarios. The primary reason for the profit decrease is that the remanufactured products do not expand the size of the market, and typically have a lower profit margin, due to lower consumer valuation. However, if  $c_2 \leq c$ , the OEM can profitably segment the market as follows; it can maintain a higher list price for the new product and thus offer the trade-in program to a larger segment of consumers, leading to higher profits. The recovered units can be sold to the  $1 - \alpha$  segment which will not purchase the new product and only purchase the remanufactured products. In addition, this helps the OEM to avoid disposal costs for the recovered products and thus, in 18.31% of the scenarios in our numerical study, the profits of the OEM increase (or remain the same) as compared to the MN case and it is optimal for the OEM to market remanufactured products. Section §4.5 provides the details of the numerical study and also identifies the product and market characteristics which determine whether marketing remanufactured products is an optimal strategy for the OEM.

Consider the most common case in the existing literature where all consumers consider purchasing a remanufactured product if available ( $\alpha = 0$ ). If the firm does not market a remanufactured product and if it can only charge a single price for the new product, the total profit is given by  $\Pi^{NN*} = \frac{(1-c)^2}{2}$ . In this case, the profit from marketing new and remanufactured products has to exceed  $\Pi^{NN*}$ , in order for the OEM to find remanufacturing profitable. In contrast, if the firm can price discriminate by offering trade-in rebates and chooses not to remanufacture, the total profit is given

by  $\Pi^{MN*} = \frac{(1-c)^2}{2} + \frac{(1-c-2s)^2}{6}$  which is strictly greater than  $\Pi^{NN*}$ . In this case, the potential profits from jointly marketing new and remanufactured products has to be much higher (as compared to the case where the OEM cannot price discriminate) to find remanufacturing profitable. Thus, for any given parameter value set, the OEM is more likely to not remanufacture when she has the opportunity to practice price discrimination through a trade-in program. This is an important finding as it helps explain why some firms do not remanufacture even though it appears they should do so based on the existing literature. We emphasize this point through the following observation.

**Observation 1** *In a market with no external competition, an OEM is more likely to not remanufacture when she has the opportunity to price discriminate through a trade-in rebate program than when she must charge a single list price for her new product.*

So what would be another incentive for the OEM to market a remanufactured product? One possibility is the threat of a third-party remanufacturer entering the market; we explore this case in the next section.

#### **4.4.3 Perfect Price Discrimination in the Presence of a Remanufactured Product Offered by a Third-Party**

We now assume that a third party enters the market in the second period and provides remanufacturing for consumers who own an older product. This may happen because many OEMs (including Alpha) believe (correctly under some scenarios, as seen in the previous section) that remanufactured products offer a cannibalization threat, and thus they refuse to market their own remanufactured product. If a consumer in the  $1 - \alpha$  segment cannot afford to purchase a new product at the list price and owns an old product, they may choose to get use the third party to get their product remanufactured.

From a modeling perspective, this case differs from the case where the OEM markets the remanufactured product in that the last two terms of (12) (where the superscript “DR” means “duopoly, remanufacturing”) are no longer part of the OEM’s objective function. Supply constraint (15) for availability of recovered units is no longer required as the OEM does not offer remanufactured products. In addition, we have a new constraint (22), i.e. only consumers who own a used product from the first-period can use the remanufacturing service offered by the third-party, i.e.  $p_1 \leq \frac{p_r}{\delta}$ . The second-period objectives of the OEM and the third-party remanufacturer are given by:

The OEM’s second-period problem is given by

$$\max_{p_{n2}} \Pi^{DR} = \alpha \left[ (1 - p_{n2})(p_{n2} - c) + \int_k^{p_{n2}} (\phi - c - s) d\phi \right] + (1 - \alpha) \left[ \left( 1 - \frac{p_{n2} - p_r}{1 - \delta} \right) (p_{n2} - c) \right] \quad (17)$$

$$s.t. \quad p_{n2} - p_r \leq 1 - \delta \quad (18)$$

$$k \doteq \max(p_1, c + s) \leq p_{n2} \quad (19)$$

The third-party remanufacturer’s second-period problem is:

$$\max_{p_r} \Pi_R^{DR} = (1 - \alpha) \frac{(\delta p_{n2} - p_r)}{\delta(1 - \delta)} (p_r - c_r) \quad (20)$$

$$s.t. \quad \delta p_{n2} - p_r \geq 0 \quad (21)$$

$$p_1 - \frac{p_r}{\delta} \leq 0 \quad (22)$$

After characterizing the OEM’s and the third-party’s optimal second-period decisions  $p_{n2}^{DR*}(p_1)$  and  $p_r^{DR*}(p_1)$  respectively, we solve for the optimal first-period decisions. In the first-period, the OEM strategically determines the first-period list price in anticipation of the second-period competition from the third-party remanufacturer. Thus, we maximize the total two-period profit of the OEM  $\Pi(p_1)^{DR} = (1 - p_1)(p_1 - c) + \Pi_2^{DR*}(p_1)$  to determine  $p_1^{DR*}$ . The sub-game perfect equilibrium in this game is described in Proposition 3.

**Proposition 3** *If the OEM offers a trade-in rebate program for new products and faces competition from a third-party remanufacturer, the OEM should always offer new products and appropriate trade-in discounts to the  $1 - \alpha$  segment. The optimal strategy for the  $1 - \alpha$  segment is defined by the following three conditions on the per-unit production cost  $c$ :*

Condition 1 : *If  $c \leq c_3$ , the OEM should offer new products and the third party does not enter the market ( $q_r^{DR*} = 0$ ,  $^{1-\alpha}q_{n2}^{DR*} > 0$ ). The optimal decisions are  $p_1^{DR*} = \frac{1+\alpha s+c(1+\alpha)}{2+\alpha}$  and  $p_{n2}^{DR*} = \frac{(1-\alpha s)(1-\delta)+c(1-\alpha)}{2-\alpha-\delta}$ .*

Condition 2 : *If  $c_3 < c < c_4$ , the OEM should offer new products and some consumers will choose to use the third party remanufacturer ( $q_r^{DR*} > 0$ ,  $^{1-\alpha}q_{n2}^{DR*} > 0$ ). The optimal decisions are summarized as follows:*

Case	$p_1^{DR*}$	$p_{n2}^{DR*}$	$p_r^{DR*}$
$c < c_e$	$\frac{1+c+\alpha c+\alpha s}{2+\alpha}$	$\frac{(1-\alpha)(2c+c_r)+2(1-\alpha s)(1-\delta)}{4-\delta-2\alpha-\alpha\delta}$	$\frac{c_r(2-\alpha-\alpha\delta)+\delta(1-\delta)(1-\alpha s)+\delta c(1-\alpha)}{4-\delta-2\alpha-\alpha\delta}$
$c_e \leq c \ \& \ \Delta_b > 0$	$\frac{1+c+\alpha c+\alpha s}{2+\alpha}$	$\frac{(1-\alpha)(2c+c_r)+2(1-\alpha s)(1-\delta)}{4-\delta-2\alpha-\alpha\delta}$	$\frac{c_r(2-\alpha-\alpha\delta)+\delta(1-\delta)(1-\alpha s)+\delta c(1-\alpha)}{4-\delta-2\alpha-\alpha\delta}$
$c_e \leq c \ \& \ \Delta_b \leq 0$	$p_1^5$	$\frac{(1-\alpha s)(1-\delta)+c(1-\alpha)+\delta p_1^5(1-\alpha)}{2-\alpha-\alpha\delta}$	$\delta p_1^5$

Condition 3 : *If  $c_4 \leq c$ , the OEM does not offer any new products and is driven out of the  $1 - \alpha$  segment by the third-party remanufacturer ( $q_r^{DR*} > 0$ ,  $^{1-\alpha}q_{n2}^{DR*} = 0$ ). The optimal decisions are summarized as follows:*

Case	$p_1^{DR*}$	$p_{n2}^{DR*}$	$p_r^{DR*}$
$c < c_f$	$\frac{1+\alpha s+c(1+\alpha)}{2+\alpha}$	$\frac{c_r+2(1-\delta)}{2-\delta}$	$\frac{c_r+\delta(1-\delta)}{2-\delta}$
$c_f \leq c$	$\frac{1+c(1+\alpha)+\alpha(s-\delta s+\delta^2)}{2+\alpha+\alpha\delta^2}$	$\frac{(1+\alpha)(1+\delta c)+(1-\delta)(1-\alpha\delta+\alpha\delta s)}{2+\alpha+\alpha\delta^2}$	$\frac{\delta(1+c(1+\alpha)+\alpha(s-\delta s+\delta^2))}{2+\alpha+\alpha\delta^2}$

The optimal solution in Proposition 3 is similar in structure to that of Proposition 2. If  $c \leq c_3$ , the new product's manufacturing cost is low enough (relative to the remanufacturing cost) and the entrant will not enter the market ( $q_r^{DR*} = 0$ ). In this case, simple algebra yields  $p_{n2}^{DR*} \leq p_{n2}^{MR*}$  which implies that the OEM has to further lower the list price for the new product (as compared to the MR case) to deter entry by the third party. This leads to a decrease in OEM's profit as compared to that under the MR case. If  $c_3 < c < c_e$  (or  $c_e \leq c \ \& \ \Delta_a > 0$ ) the production cost is higher (relative to the remanufacturing cost) and the third party enters and cannibalizes the OEM's new products sales in the  $1 - \alpha$  segment.

In this case, only a fraction of the consumers in the  $1 - \alpha$  segment purchase a new or remanufacture their old product. However, when  $c_e \leq c$  &  $\Delta_b \leq 0$ , all consumers who own an older product purchase a new product or choose to get their product remanufactured by the third party.

Finally, if  $c_4 \leq c$ , then the OEM optimal list price for the new product is too high for consumers in  $1 - \alpha$  segment to purchase a new product and the OEM is driven out of this segment. Consumers in this segment choose to get their product remanufactured by the third party. Under the threat of entry by a third party, the OEM's profit is lower than in the MR case because the OEM is giving up a portion of the market to an entrant. Although intuitive, we do not offer a formal analytical proof of this statement due to its algebraic difficulty (the profit equation is complex and has multiple regions), but we show through a numerical study in §4.5.2 which spans a realistic range of values observed in practice for the parameters in our model. As expected, the OEM's profits *never* increase in the DR case (relative to the MR case) and decrease on an average by 16.59%. This implies that although the OEM marketing remanufactured products might be a suboptimal strategy in the absence of threat of entry, it might be optimal for the OEM to market remanufactured products strategically in order to deter the entry of a third party remanufacturer. In the next section, we discuss the numerical study and identify market and product characteristics where the loss in profits for the OEM due to the third party entering the market is higher.

## 4.5 Numerical Study

We perform a numerical study to analyze whether the OEM's profits decrease (or increase) with the presence of a remanufactured product, by the OEM or entrant, relative to the monopoly case with no remanufactured product. In this section, we conduct the study for a limited but realistic range of values for the parameters. The insights obtained from this study continue to hold over the entire theoretical range of the parameters, which is shown by an extensive study, the details of which can be found in the appendix.

For the parameter  $\alpha$  we choose a full-factorial experimental design and vary it over the entire theoretical range  $[0,1]$  with values at 0.1, 0.3, 0.5, 0.7 and 0.9. Hauser and

Lund (2003) report average values of discounts of 35-55% for a remanufactured product relative to new and this number differs considerably across industries (i.e.  $\delta$  lies between 0.45 and 0.65). Guide and Li (2007) empirically find  $\delta$  for power tools and Internet routers using online auctions for both remanufactured and new products of same generation and find that  $\delta \sim 0.85$ . Subramanian and Subramanyam (2007) compare prices of new and remanufactured products (including very similar or identical warranties) and find that  $\delta$  varies from 0.60 (for video game consoles) to 0.85 (some consumer electronics). Thus, we choose to vary  $\delta$  between 0.45 and 0.95 with values at 0.45, 0.55, 0.65, 0.75, 0.85 and 0.95. Ferguson et al. (2009) develop a remanufacturing cost function based on the observation that remanufacturing costs for very good quality returns range between 20% and 28% for five different products at Pitney-Bowes. Thus, we choose to vary the remanufacturing cost as a fraction of the production cost  $c_r/c$  between 0.05 and 0.8 with values at 0.05, 0.2, 0.35, 0.5, 0.65 and 0.8.

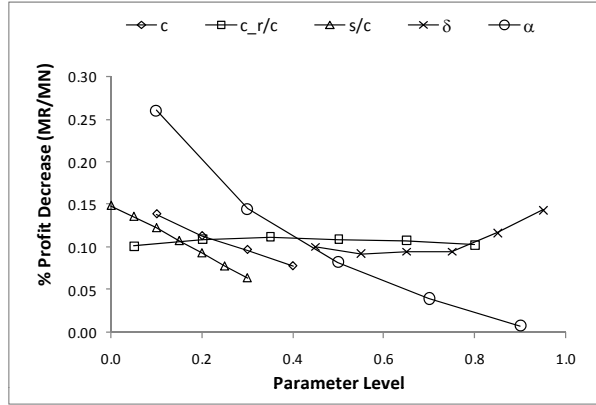
We vary the disposal cost as a fraction of the production cost  $s/c$  between 0 and 0.3 which represents range of disposal costs commonly observed in practice, with values at 0, 0.05, 0.1, 0.15, 0.2, 0.25 and 0.3. For example, in 2005, the state of California charged a recycling cost-recovery fee between \$ 6-\$ 10 for electronic products such as televisions and computer monitors (California Integrated Waste Management Board, 2008). From the model formulation, we also need the following conditions to hold;  $c + s < 1$ ,  $c_r < c$  and  $s < c$ . Based on these conditions, we vary  $c$  over its feasible range with values at 0.1, 0.2, 0.3 and 0.4. Thus, there are a total of  $5 \cdot 6^2 \cdot 4 \cdot 7 = 5,040$  experimental cells. For each experimental cell, we compute the prices, quantities and profits for the OEM for each of the three scenarios studied: the OEM has a monopoly with only the new product (MN), the OEM has a monopoly but offers new and remanufactured products (MR), a third party enters and offers remanufacturing service to consumers who own a product. We compare the OEM's profit for cases MR and DR, relative to MN. For the MN case, the OEM's profit ranges between 0.19 and 0.50, with a median value of 0.34; for the MR case, the OEM's profit ranges between 0.03 and 0.51, with a median value of 0.30; finally, for the DR case, the OEM's profit ranges between 0.09 and 0.36, with a median value of 0.20. We offer a



more detailed comparison between these cases below.

#### 4.5.1 Case MR: OEM Offers Remanufactured Product

When the OEM offers a remanufactured product, her profit increases (relative to the case MN) in only 923 out of 5,040 cells, or 18.31% of the total, with an average profit increase ( $100\% \frac{\pi^{MR*} - \pi^{MN*}}{\pi^{MN*}}$ ) in these cells of 1.73%. Profits decrease in 4,117 cells (81.69% of the cells), with an average profit decrease of 5.17%. Overall, her average profit across all cells *decreases* by 10.71%, with a maximum decrease of 84.72% and a maximum increase of 42.91%. Thus, the OEM may be worse off by offering a remanufactured product. Consequently, as discussed in §4.4.2, the OEM typically prefers not to offer a remanufactured product unless there is a threat from an entrant. To analyze which model parameters most contribute to this profit decrease, we averaged, for each factor level, the profit decrease across all corresponding cells. We then plotted the results, which are shown in Figure 4.5.1.



**Figure 8:** Average Profit Decrease when OEM Offers Remanufactured Product

Figure 4.5.1 clearly shows that the parameters that most influence profit decrease are  $\alpha$ ,  $c$  and  $s/c$ . To provide a clearer picture, we performed individual regressions, one for each experimental factor. For each regression, the dependent variable is the percent profit decrease, the independent variable is the corresponding experimental factor, and there are 5,040 observations. The magnitude of  $R^2$  for each regression provides a metric for the impact of the factor on profit decrease (Wagner, 1995), which are listed in Table 4.

**Table 4:** Individual Regression Results for Profit Deterioration - Case MR

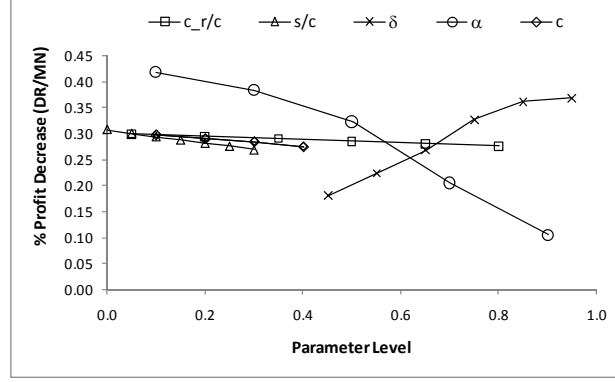
Parameter	Coefficient	$R^2$
$\alpha$	-0.305	0.448
$s/c$	-0.286	0.049
$c$	-0.199	0.03
$\delta$	0.082	0.012
$c_r/c$	0	0.001

The factors that most impact the decrease in the OEM's profit are, in order:  $\alpha$  (-),  $s/c$  (-),  $c$  (-), and to a less extent  $\delta$  and  $c_r/c$ , with  $R^2$  values of 0.448, 0.049, 0.03, 0.012, and 0.001, respectively. In particular, the factors  $\alpha$  and  $s$  account for 44.8% and 4.9%, respectively, of the variation in profit decrease. As the size of the customer segment which only considers a new product increases, it increases the ability of the OEM to practice price discrimination by offering trade-in rebates. For high values of  $\alpha$  the OEM is less hurt by the presence of a remanufactured product because many customers do not view the remanufactured product as a substitute for the new. If the fee required for disposal of a product is high, the potential loss due to cannibalization of new product sales by the remanufactured product is offset by the avoided disposal cost. Thus, for high disposal costs, the OEM has a greater incentive to market remanufactured products. The following observation captures the above results.

**Observation 2** *When the OEM has the ability to price discriminate using a trade-in rebate program, she is more likely to not market remanufactured products if the size of the consumer segment which only considers a new product is small or if the disposal fee is low.*

#### 4.5.2 Case DR: Entrant Offers Remanufactured Product

When a third party remanufacturer enters the market, the OEM's profit decreases (relative to the case MN) in all 5,040 experimental cells, as one would expect. Overall, the average profit *decrease* is 29.78%, with a maximum decrease of 58.94% and a minimum decrease of 0%. Thus, third party entry significantly worsens the OEM's profits. Again, to analyze which model parameters most contribute to this profit decrease, we have averaged, for each factor level, the profit decrease across all corresponding cells. The results are shown in Figure 9.



**Figure 9:** Average Profit Decrease when Entrant Offers Remanufactured Product

Figure 9 clearly shows that the parameters that most influence profit decrease are now  $\alpha$  and  $\delta$ . Again, we performed individual regressions, one for each experimental factor. For each regression, the dependent variable is the percent profit decrease, the independent variable is the corresponding experimental factor, and there are 5,040 observations. The results are listed in Table 5. Thus, the factors that most impact the profit decrease are, in order:  $\alpha$  (-),  $\delta$  (+),  $s/c$  (-) and to a lesser extent  $c$  (-) and  $c_r/c$  (-) with  $R^2$  values of 0.608, 0.223, 0.008, 0.003 and 0.003 respectively. In particular, the factors  $\alpha$  and  $\delta$  account for 60.8% and 22.3%, respectively, of the variation in the profit decrease.

Similar to the MR case, if the size of the consumer segment which only considers a new product is large, an OEM can offer trade-in program to more consumers. For large values of  $\alpha$  the OEM is less hurt by the presence of a third-party remanufacturer because many customers do not view the remanufactured product as a substitute for the new. Intuitively, for large values of  $\delta$ , the OEM is worse off with competition, because customers have a higher willingness-to-pay for remanufactured products, and therefore the OEM has to lower its price for a new product. Thus, when there is a threat of third-party entry, the profits of the OEM significantly decrease.

We now compare the DR case relative to MR case. That is, how much worse off is the OEM if she does not offer a remanufactured product but the third-party remanufacturer enters the market (DR), compared to the case where the OEM can preempt the entrant by offering her own version of the remanufactured product (MR). While we do not model this

**Table 5:** Individual Regression Results for Profit Deterioration - Case DR

Parameter	Coefficient	$R^2$
$\alpha$	-0.402	0.608
$\delta$	0.404	0.223
$s/c$	-0.126	0.008
$c_r/c$	-0.031	0.003
$c$	-0.0705	0.003

preemption explicitly, it is reasonable to assume the OEM may be able to do so (see the discussion in Ferguson and Toktay, 2006). Because of the OEM's established reputation and brand image, customers may strongly prefer a remanufactured product from the OEM rather than an unknown entrant.

We find the OEM's percent profit decrease ( $100\% \frac{\pi^{MR*} - \pi^{DR*}}{\pi^{MR}}$ ) from remanufacturing herself versus allowing an entrant to remanufacture is 16.59% on average, with a minimum decrease of 0% (in 7.5% of cells), a maximum decrease of 31.53%, and a median decrease of 17.78%. Thus, when there is the threat of a third-party entry, the OEM should consider marketing her own version of a remanufactured product. Although adopting such a strategy (typically) cannibalizes sales for the new product (and consequently decreases profit by an average of 10.71%), it is still optimal as the OEM is still better off than in the case where a third-party entrant offers the remanufactured product (where the average profit decrease is 29.78%). While this finding—that the OEM is better off offering a remanufactured product than letting an entrant do so— is also revealed in Ferguson and Toktay, 2006, we extend it to the case where there are trade-in rebates, perfect price discrimination, and linear remanufacturing cost; and are also the first to quantify the difference in profits resulting from the two strategies over a broad parameter set. We summarize this finding in the following observation.

**Observation 3** *An OEM is better off offering her own remanufactured products than allowing a third-party remanufacturer to do so. Such a strategy is optimal for the OEM even under cases where it is not profitable for the OEM to remanufacture in the absence of third-party competition.*

## 4.6 *Managerial Implications and Conclusions*

In this paper, we model a product that undergoes a significant redesign every few years, and study the OEM's optimal pricing strategy, along with the possibility of using trade-in rebates to provide incentives for customers to switch to a newer version of the product. We have argued, through a case study, that trade-in rebates are used to practice perfect price discrimination on customers who own a previous version of the product by offering customers customized discounts off the list price. We have shown analytically how this practice is indeed attractive to a monopolist. When the OEM faces competition from a remanufactured product (offered either by the OEM or by a third-party entrant), in addition to the cannibalization effect, the ability of the OEM to practice such price discrimination is limited. Under this scenario, we offer the following managerial insights:

1. In a monopoly market with no competition from remanufactured products, the OEM should always offer a trade-in rebate program.
2. In a market with no external competition, if all customers consider buying a remanufactured product, an OEM is more likely to not remanufacture when she has the opportunity to practice such price discrimination than when she can only charge a single list price for her new product.
3. When the OEM has the ability to price discriminate using a trade-in rebate program, she is more likely to not market remanufactured products if the size of the consumer segment which only considers a new product is small or if the disposal fee is low.
4. An OEM is better off marketing her own remanufactured products than allowing a third-party remanufacturer to do so. Such a strategy is optimal for the OEM even under cases where it is sub-optimal for the OEM to remanufacture in the absence of third-party competition.

As mentioned in the introduction, our case company Alpha has historically chosen not to remanufacture her old product, despite the abundance of used cores obtained through the trade-in rebate program. The reasons summarized in Observations 1 and 2 may partially

explain this practice. Recently, however, Alpha has observed a significant increase in the entry of third-party remanufacturers. This competitive entrance into Alpha's previously monopolistic market is a concern for two reasons: 1) the normal loss of profits because of the cannibalization of their new product sales and 2) availability of remanufactured products limits Alpha's ability to price discriminate by offering trade-in rebates to customers who cannot afford to purchase a new product at the list price. Our paper demonstrates the value to Alpha of offering her own remanufactured product to preempt third-party entrants, despite the clear cannibalization effect studied and the reduction in ability to practice price discrimination by offering customized discounts.

One limitation of this paper is that we assume that the fraction of customers who only consider buying a new product is independent of their willingness-to-pay. In practice, of course, we might expect to see a higher fraction of such customers at higher willingness-to-pay than at lower willingness-to-pay. However, we expect that extending the analysis to include such heterogeneity will only reinforce our results. Another limitation is that we assumed that the firm has perfect knowledge of the consumers willingness-to-pay for the product. It is obvious that in reality, firms can only observe this information with noise and consequently the OEM's profits from the trade-in program will be lower. Thus, similar to Choudhary et. al (2005) our results are to be interpreted as solutions to the limiting case (i.e. with perfect information). However, its an important case to consider as the insights we obtain from our analysis will also continue to hold in a general case.

## Appendix A

**Proof of Lemma 1.** Since  $d(u_n(\theta) - u_u(\theta))/d\theta > 0$ , we have that  $\Pi_\theta[L_n, r^t] - \Pi_\theta[L_u, r^t]$  and  $\Pi_\theta[L_u, r^t] - \Pi_\theta[I, r^t]$  are increasing in  $\theta$ . Thus, in equilibrium, consumers playing Ln will have higher  $\theta$  than ones playing Lu, who will have higher  $\theta$  than ones playing I. The values of  $\theta_1$  and  $\theta_2$  can be found by solving  $\Pi_\theta[L_n, r^t] = \Pi_\theta[L_u, r^t]$  and  $\Pi_\theta[L_u, r^t] = \Pi_\theta[I, r^t]$ , respectively.  $\square$

**Proof of Proposition 1.** The Hessian of the per-period profit is given by  $\begin{pmatrix} -2 & -2\delta \\ -2\delta & -2\delta \end{pmatrix}$ , whose leading coefficient is negative and the determinant  $4\delta(1 - \delta)$  is positive. Thus, the hessian is negative definite and the per-period profit function is jointly strictly concave in  $L_n$  and  $L_u$ .

Now assume that Assumption A1 holds. The inverse demand functions for the new and used product leases can be found by substituting  $u_n(\theta) = \theta$  and  $u_u(\theta) = \delta\theta$  and solving (1),  $L_n = 1 - \theta_1$  and  $L_u = \theta_1 - \theta_2$  simultaneously. The firm's per-period problem at steady state is given by

$$\begin{aligned} \max_{L_n, L_u} (r_n - c)L_n + (r_u - \beta_f)L_u - s_f L_n &= (1 - L_n - \delta L_u - c)L_n \\ &+ (\delta(1 - L_n - L_u) - \beta_f)L_u - s_f L_n \\ \text{s.t. } L_u &\leq L_n \text{ and } L_n, L_u \geq 0. \end{aligned}$$

The Lagrangean is given by

$$\begin{aligned} \mathbb{L}(L_n, L_u) &= (1 - L_n - \delta L_u - c)L_n + (\delta(1 - L_n - L_u) - \beta_f)L_u - s_f L_n - \lambda(L_u - L_n) \\ &+ \mu_1 L_n + \mu_2 L_u, \end{aligned}$$

with first-order conditions

$$\begin{aligned} \sigma_1(L_n, L_u, \lambda, \mu_1) &\doteq \frac{\partial \mathbb{L}}{\partial L_n} = 1 + \lambda + \mu_1 - c - 2L_n - s_f - 2\delta L_u = 0 \text{ and} \\ \sigma_2(L_n, L_u, \lambda, \mu_2) &\doteq \frac{\partial \mathbb{L}}{\partial L_u} = \delta + \mu_2 - \beta_f - 2\delta(L_n + L_u) - \lambda = 0. \end{aligned}$$

Since the per-period profit function is strictly concave in  $L_n$  and  $L_u$ , the necessary and sufficient conditions for optimality (Kuhn-Tucker conditions) are that the first order conditions (FOC) are satisfied and  $\lambda(L_u - L_n) = 0$ ,  $\mu_1 L_n = 0$ ,  $\mu_2 L_u = 0$ ,  $\lambda \geq 0$ ,  $\mu_1 \geq 0$  and  $\mu_2 \geq 0$ . There are four candidate solutions to the optimization problem defined as cases 1-4 below.

Case 1.  $L_n > 0$  and  $0 < L_u = L_n$ . Then  $\mu_1 = 0$  and  $\mu_2 = 0$ . Solving  $\sigma_1(L_n, L_n, \lambda, 0) = 0$  and  $\sigma_2(L_n, L_n, \lambda, 0) = 0$  gives  $L_n = \frac{1-c-s_f-\beta_f+\delta}{2+6\delta}$  and  $\lambda = \frac{2\delta s_f - \beta_f(1+\delta) - \delta(1-2c-\delta)}{1+3\delta}$ .  $\lambda \geq 0$  and  $L_n > 0$  hold for  $\frac{\beta_f(1+\delta)+\delta(1-2c-\delta)}{2\delta} \leq s_f$  and  $c+s_f+\beta_f < 1+\delta$ , respectively. Since according to our assumption,  $c + \max(s_c, s_f) + \beta_f < 1$  and  $\delta > 0$ ,  $c+s_f+\beta_f < 1+\delta$  clearly holds. Thus, the required condition for this case to apply is  $\frac{\beta_f(1+\delta)+\delta(1-2c-\delta)}{2\delta} \leq s_f$ .

Case 2.  $L_n > 0$  and  $0 < L_u < L_n$ . Then  $\mu_1 = 0$ ,  $\mu_2 = 0$  and  $\lambda = 0$ . Solving  $\sigma_1(L_n, L_n, 0, 0) = 0$  and  $\sigma_2(L_n, L_n, 0, 0) = 0$  gives  $L_n = \frac{1-c-s_f+\beta_f-\delta}{2(1-\delta)}$  and  $L_u = \frac{\delta(c+s_f)-\beta_f}{2\delta(1-\delta)}$ .  $L_n > 0$ ,  $L_u > 0$  and  $L_u < L_n$  hold for  $s_f < 1-c+\beta_f-\delta$ ,  $\frac{\beta_f-\delta c}{\delta} < s_f$  and  $s_f < \frac{\beta_f(1+\delta)+\delta(1-2c-\delta)}{2\delta}$ , respectively. Since  $\frac{\beta_f(1+\delta)+\delta(1-2c-\delta)}{2\delta} - (1-c+\beta_f-\delta) < 0$  for  $c+s_f+\beta_f < 1$ , if  $s_f < \frac{\beta_f(1+\delta)+\delta(1-2c-\delta)}{2\delta}$  holds, then  $s_f < 1-c+\beta_f-\delta$  also holds. Thus, the required condition for this case to apply is  $\frac{\beta_f-\delta c}{\delta} < s_f < \frac{\beta_f(1+\delta)+\delta(1-2c-\delta)}{2\delta}$ .

Case 3.  $L_n > 0$  and  $L_u = 0$ . Then  $\mu_1 = 0$  and  $\lambda = 0$ . Solving  $\sigma_1(L_n, 0, 0, 0) = 0$  and  $\sigma_2(L_n, 0, 0, \mu_2) = 0$  gives  $L_n = \frac{1-c-s_f}{2}$  and  $\mu_2 = \beta_f - \delta(c+s_f)$ .  $\mu_2 \geq 0$  and  $L_n > 0$  hold for  $s_f \leq \frac{\beta_f-\delta c}{\delta}$  and  $c+s_f < 1$ , respectively. Since according to our assumption,  $c + \max(s_c, s_f) + \beta_f < 1$ ,  $c+s_f < 1$  clearly holds. Thus, the required condition for this case to apply is  $s_f \leq \frac{\beta_f-\delta c}{\delta}$ .

Case 4.  $L_n = 0$  and  $L_u = 0$ . Solving  $\sigma_1(0, 0, \lambda, \mu_1) = 0$  and  $\sigma_2(0, 0, \lambda, \mu_2) = 0$  gives  $\mu_1 = -1+c+s_f-\lambda$  and  $\mu_2 = \beta_f - \delta + \lambda$ .  $\mu_1 \geq 0$  holds for  $\lambda \leq -(1-c-s_f)$ . However, according to our assumption,  $c + \max(s_c, s_f) + \beta_f < 1$ ,  $(1-c-s_f) > 0$ . This implies that  $\mu_1 \geq 0$  and  $\lambda \geq 0$  cannot hold together and this case is ruled out.

The three remaining candidate solutions and the required conditions for each of them can be summarized as follows: If  $s_f \leq \frac{\beta_f-\delta c}{\delta}$ , then  $L^* = \left(\frac{1-c-s_f}{2}, 0\right)$ , if  $\frac{\beta_f-\delta c}{\delta} < s_f < \frac{\beta_f(1+\delta)+\delta(1-2c-\delta)}{2\delta}$ , then  $L^* = \left(\frac{1-c-s_f+\beta_f-\delta}{2(1-\delta)}, \frac{\delta(c+s_f)-\beta_f}{2\delta(1-\delta)}\right)$  and if  $\frac{\beta_f(1+\delta)+\delta(1-2c-\delta)}{2\delta} \leq s_f$ , then  $L^* = \left(\frac{1-c-s_f-\beta_f+\delta}{2+6\delta}, \frac{1-c-s_f-\beta_f+\delta}{2+6\delta}\right)$ .  $\square$

**Proof of Lemma 2.** We suppress the selling-specific notation for this proof. There are



nine potential two-period consumer strategies as shown in Table 1. At the focal point, the consumer's Bellman equation can be written as

$$V_\theta[a(\theta), p] = \max_{a(\theta)} \{\Pi_\theta[R_\theta[a(\theta), p]; a(\theta), p] + \rho V_\theta[R_\theta[a(\theta), p], p]\} \quad (23)$$

Since a product lasts two periods, a rational consumer who has a state of  $Bu$  or  $I$ , will choose the same action in the current period as they enter the period with no product. This implies that at the focal point,

$$R_\theta[Bu, p] = R_\theta[I, p] \text{ and } V_\theta[Bu, p] = V_\theta[I, p]. \quad (24)$$

Due to the periodicity of two for all consumer strategies at the focal point, permutations of same pattern are not distinct. There are only 6 distinct strategies (BnBn, BnBu, BnI, BuBu, BuI and II). From (24),  $V_\theta[Bu, p] = V_\theta[I, p]$  and examining (23), it is easy to see that if a consumer chose Bu or I in the previous period, it will still find it optimal to choose the same strategy in the current period. This implies that BuI cannot happen in equilibrium. Thus, there are only 5 possible strategies left. We next prove that at the focal point, BnI cannot happen.

Recall that the reaction function  $R_\theta[a(\theta), p]$  is chosen to maximize

$$U_\theta[s; a, p] \equiv \Pi_\theta[s; a, p] + \rho V_\theta[s, p]. \quad (25)$$

Let us assume that BnI is a credible strategy, which implies that  $R_\theta[Bn, p] = I$  and  $R_\theta[I, p] = Bn$  for some  $\theta \in [0, 1]$ . Note that  $R_\theta[Bn, p] = I$  implies that

$$\begin{aligned} p_u - \beta_c + \rho V_\theta[I, p] &> u_n(\theta) - p_n + p_u - \beta_c + \rho V_\theta[Bn, p] \\ \text{or } \rho V_\theta[I, p] &> u_n(\theta) - p_n + \rho V_\theta[Bn, p]. \end{aligned}$$

However, the above equation implies that  $U_\theta[I; I, p] > U_\theta[Bn; I, p] \Rightarrow R_\theta[I, p] = I$ . Thus, if a consumer plays I when he is in state Bn, then it will be optimal for him to always play I thereafter. This violates our assumptions and thus, BnI cannot take place. Thus, there are four possible strategies at the focal point. Consumers who play BnBn will have higher  $\theta$  than those who play BnBu, who have higher  $\theta$  than those who play BuBu. Consumers

playing II will have the lowest willingness-to-pay. The net present values for each of the four consumption strategies BnBn, BnBu, BuBu and II at the focal point are given as follows:

$$V_\theta[Bn, p] = \frac{u_n(\theta) - p_n + p_u - \beta_c}{1 - \rho} \quad \text{when } \theta \in (\theta_5, 1] \text{ or } \theta \in BnBn, \quad (26)$$

$$V_\theta[Bn, p] = \frac{u_u(\theta) - s_c + \rho(u_n(\theta) - p_n)}{1 - \rho^2} \quad \text{when } \theta \in (\theta_6, \theta_5] \text{ or } \theta \in BnBu, \quad (27)$$

$$V_\theta[Bu, p] = \frac{u_n(\theta) - p_n + \rho(u_u(\theta) - s_c)}{1 - \rho^2} \quad \text{when } \theta \in (\theta_6, \theta_5] \text{ or } \theta \in BnBu, \quad (28)$$

$$V_\theta[Bu, p] = \frac{u_u(\theta) - p_u - s_c}{1 - \rho} \quad \text{when } \theta \in (\theta_7, \theta_6] \text{ or } \theta \in BuBu, \quad (29)$$

$$V_\theta[I, p] = 0 \quad \text{when } \theta \in (0, \theta_7] \text{ or } \theta \in II. \quad (30)$$

The value of  $\Theta_3$  can be found by equating (29) and (30), the value of  $\Theta_2$  can be found by equating (27) and (29) and finally, the value of  $\Theta_1$  can be found by equating (26) and (27).

□

**Proof of Proposition 2.** Under Assumption A1, it is easy to show using (5) and (6) that the per-period profit function is strictly concave in  $S_n$ . Solving for the first-order conditions yields  $S_n^*$ .

**Proofs of Lemma 3 and Propositions 3-5.** These follow directly by comparing the expressions for the optimal decisions and profits obtained in Sections 2.3.1 and 2.3.2.

## Appendix B

### B1. Proofs

**Proof of Lemma 1.** It is easy to see that under our consumer model,  $\Pi_\theta[(1, 0, 0); p^t, j]$ ,  $\Pi_\theta[(0, 1, 0); p^t, j]$  and  $\Pi_\theta[(0, 0, 1); p^t, j]$  are linear, monotonic and increasing functions of  $\theta$ . Moreover,  $\Pi_\theta[(1, 0, 0); p^t, j] - \Pi_\theta[(0, 1, 0); p^t, j]$  and  $\Pi_\theta[(0, 1, 0); p^t, j] - \Pi_\theta[(0, 0, 1); p^t, j]$  are increasing in  $\theta$ . Thus, in equilibrium, customers buying a new product will have higher  $\theta$  than ones buying a remanufactured product, who will have higher  $\theta$  than ones remaining inactive. In the absence of remanufactured products,  $\theta_1$  can be found by solving  $u_n(\theta_1, x) - p_n^t = 0$  and the demand for new products is given by  $q_n^t(p_n^t) = 1 - \theta_1$ . In the presence of remanufactured products ( $j = o$  or  $j = 3p$ ),  $\Theta_1$  and  $\Theta_2$  can be found by solving  $u_r(\Theta_2, j) - p_r^t = 0$  and  $u_n(\Theta_1, j) - p_n^t = u_r(\Theta_1, j) - p_r^t$  simultaneously and the demand for new and remanufactured products is given by  $q_n^t(p_n^t, p_r^t) = 1 - \Theta_1$  and  $q_r^t(p_n^t, p_r^t) = \Theta_1 - \Theta_2$ .  $\square$

**Proof of Proposition 1.** This proof is structured as follows: First, we characterize the OEM's optimal steady-state policy when it only sells new products and when it chooses to remanufacture its own products. We finally compare the profitability of these two cases to determine when the OEM will find it profitable to remanufacture.

Characterizing the optimal decisions under no remanufacturing (X) and remanufacturing (R): If the OEM only sells new products, the demand function for the new products can be found by substituting  $j = x$ ,  $u_n(\theta, x) = \theta$ , solving equation  $u_n(\theta_1, x) - p_n^t = 0$  and  $\bar{q}_n = 1 - \theta_1$  simultaneously and is given by  $\bar{q}_n = 1 - \bar{p}_n$ . The per-period profit is given by  $\bar{\Pi} = (\bar{p}_n - c)(1 - \bar{p}_n)$ , which is strictly concave in  $\bar{p}_n$ .  $\bar{p}_n^* = \frac{1+c}{2}$ ,  $\bar{q}_n^* = \frac{1-c}{2}$  and  $\bar{\Pi}_X^* = \frac{(1-c)^2}{4}$ .

If the OEM decides to remanufacture, the demand functions can be found by substituting  $j = o$ ,  $u_n(\theta, o) = \beta\theta$  and  $u_r(\theta, o) = \phi_o\theta$ , solving the system of equations  $u_r(\Theta_2, j) - p_r^t = 0$  and  $u_n(\Theta_1, j) - p_n^t = u_r(\Theta_1, j) - p_r^t$ ,  $\bar{q}_n(\bar{p}_n, \bar{p}_r) = 1 - \Theta_1$  and  $\bar{q}_r(\bar{p}_n, \bar{p}_r) = \Theta_1 - \Theta_2$  simultaneously and are given by  $\bar{q}_n(\bar{p}_n, \bar{p}_r) = \frac{\beta - \bar{p}_n - \phi_o + \bar{p}_r}{\beta - \phi_o}$  and  $\bar{q}_r(\bar{p}_n, \bar{p}_r) = \frac{\phi_o \bar{p}_n - \beta \bar{p}_r}{\phi_o(\beta - \phi_o)}$ . The hessian of the per-period profit is given by  $\begin{pmatrix} -2/(\beta - \phi_o) & -2\beta/\phi_o(\beta - \phi_o) \\ -2\beta/\phi_o(\beta - \phi_o) & -2\beta/\phi_o(\beta - \phi_o) \end{pmatrix}$ , whose leading coefficient is negative and the determinant  $4/\phi_o(\beta - \phi_o)$  is positive (since  $\phi_o < \beta$

in our consumer model). Thus, the hessian is negative definite and the per-period profit function is jointly strictly concave in  $\bar{q}_n$  and  $\bar{q}_r$ . The OEM's steady-state problem under remanufacturing ( $\bar{q}_r(\bar{p}_n, \bar{p}_r) > 0$ ), is given by  $\max_{\bar{p}_n, \bar{p}_r} (\bar{p}_n - c)\bar{q}_n(\bar{p}_n, \bar{p}_r) + (\bar{p}_r - h_o)\bar{q}_r(\bar{p}_n, \bar{p}_r)$ , s.t.  $0 < \bar{q}_r(\bar{p}_n, \bar{p}_r) \leq \bar{q}_n(\bar{p}_n, \bar{p}_r)$  and  $\bar{q}_n(\bar{p}_n, \bar{p}_r) \geq 0$ . Since  $\bar{q}_r(\bar{p}_n, \bar{p}_r) > 0$  and  $\bar{q}_r(\bar{p}_n, \bar{p}_r) \leq \bar{q}_n(\bar{p}_n, \bar{p}_r)$ , there are only two candidate solutions:

Case 1.  $0 < \bar{q}_r(\bar{p}_n, \bar{p}_r) = \bar{q}_n(\bar{p}_n, \bar{p}_r)$ . It is easy to show that this case applies only if  $h_o \leq \bar{h}_a(\beta, \phi_o, c) \doteq \frac{2c\phi_o - \beta\phi_o + \phi_o^2}{\beta + \phi_o}$  and under this case,  $\bar{p}_n = \frac{\beta(\beta + h_o + c) + \phi_o(4\beta + h_o + c) - \phi_o^2}{2(\beta + 3\phi_o)}$ ,  $\bar{p}_r = \frac{\phi_o(2\phi_o + h_o + c)}{\beta + 3\phi_o}$  and  $\bar{\Pi}_R = \frac{(\beta - c + \phi_o - h_o)^2}{4(\beta + 3\phi_o)}$ .

Case 2.  $0 < \bar{q}_r(\bar{p}_n, \bar{p}_r) < \bar{q}_n(\bar{p}_n, \bar{p}_r)$ . It is easy to show that this case applies only if  $\bar{h}_a(\beta, \phi_o, c) < h_o < \bar{h}_b(\beta, \phi_o, c) \doteq \frac{c\phi_o}{\beta}$  and under this case,  $\bar{p}_n = \frac{\beta + c}{2}$ ,  $\bar{p}_r = \frac{\phi_o + h_o}{2}$  and  $\bar{\Pi}_R = \frac{\beta h_o^2 - 2ch_o\phi_o + \phi_o((\beta - c)^2 + \phi_o(2c - \beta))}{4\phi_o(\beta - \phi_o)}$ .

*Step 3: When is Remanufacturing Profitable?* Let  $\Pi_X$  and  $\Pi_R$  denote the per-period profit under no remanufacturing and remanufacturing, respectively. Since  $\bar{\Pi}_X^* - \bar{\Pi}_R^*$  evaluated at  $h_o = \bar{h}_b(\beta, \phi_o, c)$  is given by  $\frac{(\beta - c^2)(1 - \beta)}{4\beta}$  which is positive under our consumer model,  $\bar{\Pi}_X^*$  is independent of  $h_o$  and  $\bar{\Pi}_R^*$  is decreasing in  $h_o$ , we have that there exists a unique value of  $h_o$  such that  $\bar{\Pi}_X^* = \bar{\Pi}_R^*$  and is given by  $\bar{h}(\beta, \phi_o, c) \doteq \beta - c + \phi_o - (1 - c)\sqrt{\beta + 3\phi_o}$ . If  $h_o \leq \bar{h}(\beta, \phi_o, c)$ ,  $\bar{\Pi}_R^* \geq \bar{\Pi}_X^*$ , remanufacturing is profitable for the OEM, and otherwise,  $\bar{\Pi}_R^* < \bar{\Pi}_X^*$ , only selling new products is profitable. Under  $\bar{h}(\beta, \phi_o, c) \geq 0$ ,  $\beta \in [\phi_o, 1]$   $\phi_o \in [0, \beta]$  and  $c \in [0, \beta]$  (under our consumer model), it is easy to show that  $d\bar{h}(\cdot)/d\beta \geq 0$ ,  $d\bar{h}(\cdot)/d\phi_o \geq 0$ , and  $d\bar{h}(\cdot)/dc \geq 0$ , which implies that  $\bar{h}(\beta, \phi_o, c)$  is increasing in  $\beta$ ,  $\phi_o$  and  $c$ .  $\square$

**Proof of Proposition 2.** The demand functions can be found by substituting  $j = 3p$ ,  $u_n(\theta, 3p) = \alpha\theta$  and  $u_r(\theta, 3p) = \phi_{3p}\theta$ , solving equations  $u_r(\Theta_2, j) - p_r^t = 0$ ,  $u_n(\Theta_1, j) - p_n^t = u_r(\Theta_1, j) - p_r^t$ ,  $q_n(p_n, p_r) = 1 - \Theta_1$  and  $q_r(p_n, p_r) = \Theta_1 - \Theta_2$  simultaneously and are given by  $q_n(p_n, p_r) = \frac{\alpha - p_n - \phi_{3p} + p_r}{\alpha - \phi_{3p}}$  and  $q_r(p_n, p_r) = \frac{\phi_{3p}p_n - \alpha p_r}{\phi_{3p}(\alpha - \phi_{3p})}$ . The per-period profit of the OEM is  $\Pi_o(p_n|p_r) = (p_n - c)q_n(p_n, p_r)$  and since  $\Pi_o'' = -2/(\alpha - \phi_{3p}) < 0$  (since  $\alpha > \phi_{3p}$  under our consumer model),  $\Pi_o(p_n|p_r)$  is strictly concave in  $p_n$ . The per-period profit of the third-party remanufacturer is  $\Pi_{3p}(p_r|p_n) = (p_r - h_{3p})q_r(p_n, p_r)$  and since  $\Pi_{3p}'' = -2\alpha/\phi_{3p}(\alpha - \phi_{3p}) < 0$  (since  $\alpha > \phi_{3p}$  under our consumer model),  $\Pi_{3p}(p_r|p_n)$  is strictly concave in  $p_r$ .

The OEM's problem at the steady state is:  $\max_{p_n} \Pi_o(p_n|p_r)$  s.t.  $q_n(p_n, p_r) \geq 0$  and the third-party remanufacturer's steady-state problem is  $\max_{p_r} \Pi_{3p}(p_r|p_n)$  s.t.  $0 \leq q_r(p_n, p_r) \leq q_n(p_n, p_r)$ . Since we assumed that  $c \leq \beta$ ,  $h_o \leq \phi_o$  and  $h_{3p} \leq \phi_{3p}$ , it is easy to see that the case  $q_n(p_n, p_r) = q_r(p_n, p_r) = 0$  is ruled out. Since we are interested in when the third party enters ( $q_r(p_n, p_r) > 0$ ), there are two candidate solutions:

Case 1.  $0 < q_r(p_n, p_r) = q_n(p_n, p_r)$ . It is easy to show that this case applies only if  $h_{3p} \leq h_a(\alpha, \phi_{3p}, c) \doteq \frac{\alpha\phi_{3p}(3c-\alpha)+(\alpha-c)\phi_{3p}^2}{2\alpha^2}$  and under this case,  $p_n = \frac{\alpha(\alpha-\phi_{3p})+c(\alpha+\phi_{3p})}{2\alpha}$ ,  $p_r = \frac{c\phi_{3p}}{\alpha}$ ,  $\Pi_o = \frac{(\alpha-c)^2(\alpha-\phi_{3p})}{4\alpha^2}$  and  $\Pi_{3p} = \frac{(\alpha-c)(c\phi_{3p}-h_{3p}\alpha)}{2\alpha^2}$ .

Case 2.  $0 < q_r(p_n, p_r) < q_n(p_n, p_r)$ . It is easy to show that this case applies only if  $h_a(\alpha, \phi_{3p}, c) < h_{3p} < h_b(\alpha, \phi_{3p}, c) \doteq \frac{\phi_{3p}(\alpha+c-\phi_{3p})}{2\alpha-\phi_{3p}}$  and under this case,  $p_n = \frac{\alpha(2c+h_{3p}+2\alpha-2\phi_{3p})}{4\alpha-\phi_{3p}}$ ,  $p_r = \frac{2h_{3p}\alpha+\phi_{3p}(c+\alpha-\phi_{3p})}{4\alpha-\phi_{3p}}$ ,  $\Pi_o = \frac{(\alpha(2\alpha-2\phi_{3p}+h_{3p})-c(2\alpha-\phi_{3p}))^2}{(\alpha-\phi_{3p})(4\alpha-\phi_{3p})^2}$  and  $\Pi_{3p} = \frac{\alpha(\phi_{3p}(\alpha+c-\phi_{3p})-h_{3p}(2\alpha-\phi_{3p}))^2}{\phi_{3p}(\alpha-\phi_{3p})(4\alpha-\phi_{3p})^2}$ .

Based on Case 2, it is easy to see that  $q_r > 0$  only holds if  $h_{3p} < h_b(\alpha, \phi_{3p}, c)$ . Thus, the third-party remanufacturer will only compete with the OEM if  $h_{3p} < h_b(\alpha, \phi_{3p}, c)$ .  $\square$

**Proof of Proposition 3.** Let  $h_{3p} < h_b(\alpha, \phi_{3p}, c)$  (third-party remanufacturer finds it profitable to compete) and assume that the OEM is restricted to only sell new products. The OEM's profit under no remanufacturing is given by  $\Pi_X = \frac{(1-c)^2}{4}$  and we know from Proposition 2, that in the presence of remanufacturing by the third party (denoted by 3P) is given by  $\Pi_{3P} = \frac{(\alpha-c)^2(\alpha-\phi_{3p})}{4\alpha^2}$ , if  $h_{3p} \leq h_a(\alpha, \phi_{3p}, c)$  and  $\Pi_{3P} = \frac{(\alpha(2\alpha-2\phi_{3p}+h_{3p})-c(2\alpha-\phi_{3p}))^2}{(\alpha-\phi_{3p})(4\alpha-\phi_{3p})^2}$ , if  $h_a(\alpha, \phi_{3p}, c) \leq h_{3p} < h_b(\alpha, \phi_{3p}, c)$ . We are interested in comparing  $\Pi_X$  and  $\Pi_{3P}$  and we will do it in two stages:  $h_{3p} \leq h_a(\alpha, \phi_{3p}, c)$  and  $h_a(\alpha, \phi_{3p}, c) \leq h_{3p} < h_b(\alpha, \phi_{3p}, c)$ .

Consider  $h_{3p} \leq h_a(\alpha, \phi_{3p}, c)$ . Let  $x_1(c) \doteq \Pi_{3P} - \Pi_X$ . This function is concave:  $x_1''(c) = -\frac{\alpha(\alpha-1)+\phi_{3p}}{2\alpha^2} < 0$ . Under our consumer model and the assumption  $c \leq \beta \leq 1$ ,  $x_1(c)$  switches from negative to positive only once over  $c \in [0, 1]$  because  $x_1(c) = 0$  has two roots  $c_1(\alpha, \phi_{3p})$  and  $c_2(\alpha, \phi)$ , s.t.  $c_1(\alpha, \phi_{3p}) \leq 1 \leq c_2(\alpha, \phi)$ . Moreover,  $x_1(1) = \frac{(\alpha-1)^2(\alpha-\phi_{3p})}{4\alpha^2} \geq 0$  (or  $\Pi_{3P} \geq \Pi_X$ ). Therefore, there exists a unique  $c_1(\alpha, \phi_{3p}) \leq 1$  such that if  $c \leq c_1(\alpha, \phi_{3p})$ , the presence of manufacturing competition lowers OEM's profitability. Otherwise, the presence of remanufacturing competition leads to higher OEM profitability. Under our consumer model ( $\alpha \in [1, 2]$  and  $\phi_{3p} \in [0, 1]$ ), it is easy to show  $dc_1(\cdot)/d\alpha \leq 0$  and  $dc_1(\cdot)/d\phi_{3p} \geq 0$  which implies that  $c_1(\alpha, \phi_{3p})$  is decreasing in  $\alpha$  but increasing in  $\phi_{3p}$ .

Consider  $h_a(\alpha, \phi_{3p}, c) < h_{3p} < h_b(\alpha, \phi_{3p}, c)$ . Let  $x_2(h_{3p}) = \Pi_{3P} - \Pi_X$ .  $x_2'(h_{3p}) = \frac{2\alpha(\alpha(h_{3p}+2\alpha-2\phi_{3p})-c(2\alpha-\phi_{3p}))}{\alpha}$  which is positive for  $h_{3p} > \frac{2c\alpha-2\alpha^2-c\phi_{3p}+2\alpha\phi_{3p}}{\alpha}$ . Since this condition always holds for  $h_a(\alpha, \phi_{3p}, c) < h_{3p}$ , we have that  $x_2(h_{3p})$  is increasing in  $h_{3p}$ . The positive value of  $h_{3p}$  such that  $x_2(h_{3p}) = 0$ , is given by  $h_0(\alpha, \phi_{3p}, c) \doteq \frac{(1-c)(4\alpha-\phi_{3p})\sqrt{\alpha-\phi_{3p}}}{2\alpha} + 2(c + \phi_{3p}) - \frac{2\alpha^2+c\phi_{3p}}{\alpha}$ . Thus, if  $h_a(\alpha, \phi_{3p}, c) < h_{3p} \leq \min(h_0(\alpha, \phi_{3p}, c), h_b(\alpha, \phi_{3p}, c))$ , then  $\Pi_{3P} \leq \Pi_X$ . Otherwise, if  $h_0(\alpha, \phi_{3p}, c) < h_{3p} < h_b(\alpha, \phi_{3p}, c)$ , remanufacturing competition leads to higher OEM profitability. Under our consumer model ( $\alpha \in [1, 2]$ ,  $\phi_{3p} \in [0, 1]$  and  $c \in [0, 1]$ ), it is easy to show that  $dh_0(\cdot)/d\phi_{3p} \geq 0$  and  $dh_0(\cdot)/d\alpha \leq 0$  which imply that  $h_0(\alpha, \phi_{3p}, c)$  is increasing in  $\phi_{3p}$  but decreasing in  $\alpha$ .

Let  $h_1(\alpha, \phi_{3p}, c) \doteq \max(h_0(\alpha, \phi_{3p}, c), h_a(\alpha, \phi_{3p}, c))$ . Summarizing the above results, if  $c > c_1(\alpha, \phi_{3p})$  or  $h_{3p} > h_1(\alpha, \phi_{3p}, c)$ , then OEM's profitability is higher in the presence of remanufacturing competition.  $\square$

**Proof of Proposition 4.** Consider the situation when the third party finds it profitable to compete with the OEM, i.e.,  $h_{3p} < h_b(\alpha, \phi_{3p}, c)$ . We will first compare the profitability of different strategies pairwise and then summarize for the OEM's optimal strategy. Let  $\Pi_R$ ,  $\Pi_{3P}$  and  $\Pi_{PC}$  denote the per-period profit under preemptive remanufacturing, letting the third party remanufacture and preemptive collection, respectively.

*Step 1: Comparing profitability of R and PC Strategies.* The analysis for this comparison can be obtained by replicating the proof of Proposition 1, with  $\Pi_o^X = \frac{(1-c)^2}{4}$  replaced with  $\Pi_o^{PC} = \frac{(1-c-s)^2}{4}$ . This is because under preemptive collection, the OEM does not remanufacture and has to collect and dispose at a cost of  $s$  per unit. Thus, it follows that there exists  $\bar{h}_s(\beta, \phi_o, c, s) > \bar{h}(\beta, \phi_o, c)$  s.t. remanufacturing is more profitable, only if  $h_o \leq \bar{h}_s(\beta, \phi_o, c, s)$ .

*Step 2: Comparing profitability of PC and 3P Strategies.* The analysis for this comparison can be obtained by replicating the proof of Proposition 3, with  $\Pi_o^X = \frac{(1-c)^2}{4}$  replaced with  $\Pi_o^{PC} = \frac{(1-c-s)^2}{4}$ . Thus, it follows that there exists  $c_{1s}(\alpha, \phi_{3p}, s)$  and  $h_{1s}(\alpha, \phi_{3p}, c, s)$ , if  $c > c_{1s}(\alpha, \phi_{3p}, s)$  or  $h_{3p} > h_{1s}(\alpha, \phi_{3p}, c, s)$  (where  $c_1(\alpha, \phi_{3p}) > c_{1s}(\alpha, \phi_{3p}, s)$  and  $h_1(\alpha, \phi_{3p}, c) > h_{1s}(\alpha, \phi_{3p}, s)$ ) letting the third party remanufacture is more profitable than preemptive collection.

*Step 3: Comparing profitability of R and 3P Strategies.* Without loss of generality, let  $h_{3p} = \gamma h_o$ , where  $\gamma \geq 0$ . Recall that the OEM's profit under a remanufacturing strategy,  $\Pi_R$  is given by  $\frac{(\beta + \phi_o - h_o - c)^2}{4(\beta + 3\phi_o)}$  if  $h_o \leq \bar{h}_a$  and by  $\frac{\beta h_o^2 - 2ch_o\phi_o + \phi_o((\beta - c)^2 + \phi_o(2c - \beta))}{4\phi_o(\beta - \phi_o)}$  if  $\bar{h}_a < h_o < \bar{h}_b$ . It is easy to see that  $\Pi_R$  is weakly decreasing in  $h_o$ . The OEM's profit when the third party remanufactures,  $\Pi_{3P}$ , is given by  $\frac{(\alpha - c)^2(\alpha - \phi_{3p})}{4\alpha^2}$ , if  $\gamma h_o \leq h_a(\alpha, \phi_{3p}, c)$  and  $\frac{(\alpha(2\alpha - 2\phi_{3p} + \gamma h_o) - c(2\alpha - \phi_{3p}))^2}{(\alpha - \phi_{3p})(4\alpha - \phi_{3p})^2}$ , if  $h_a(\alpha, \phi_{3p}, c) \leq \gamma h_o$ . It is easy to see that  $\Pi_{3P}$  is weakly increasing in  $h_o$ . Thus, there exists a  $h_{2s}(\alpha, \phi_o, \phi_{3p}, c, \gamma)$  such that  $\Pi_{3P} = \Pi_R$ . If  $h_o \leq h_{2s}(\alpha, \phi_o, \phi_{3p}, c, \gamma)$ , then  $\Pi_R \geq \Pi_{3P}$  and if  $h_{2s}(\alpha, \phi_o, \phi_{3p}, c, \gamma) < h_o$ , then  $\Pi_R < \Pi_{3P}$ . Since  $h_{3p} = \gamma h_o$ , we can redefine this threshold such that if  $h_o \leq h_2(\alpha, \phi_o, \phi_{3p}, c, h_{3p})$ , then it is profitable for the OEM to remanufacture and if  $h_2(\alpha, \phi_o, \phi_{3p}, c, h_{3p}) < h_o$ , then the OEM should let the third party remanufacture.

*Step 4: Summarizing OEM's optimal strategy.* Combining the results from Steps 1-3 above, we have that preemptive remanufacturing is optimal if  $h_o \leq h^-(\alpha, \beta, \phi_o, \phi_{3p}, c, h_{3p}, s) \doteq \min(\bar{h}_s(\beta, \phi_o, c, s), h_2(\alpha, \phi_o, \phi_{3p}, c, h_{3p}))$ . If  $h^-(\alpha, \beta, \phi_o, \phi_{3p}, c, h_{3p}, s) < h_o$ : Now if  $h_{3p} \leq h^+(\alpha, \phi_{3p}, c, s) \doteq h_{1s}(\alpha, \phi_{3p}, c, s)$  and  $c \leq c^-(\alpha, \phi_{3p}, s) \doteq c_{1s}(\alpha, \phi_{3p}, s)$ , then preemptive collection is optimal. Otherwise, letting the third party remanufacture is optimal.  $\square$

**B2. Effect of Positive Fixed Costs of Collection or Remanufacturing.** If the remanufacturable cores cannot be inventoried and there exist fixed costs for collection  $F_c$  or remanufacturing  $F_r$  for the OEM: Proposition 1 would remain the same unless  $\Pi_R - \Pi_X < F_r$ , when remanufacturing will never be profitable. The structure of Proposition 4 and Figure 6 would change only if  $\Pi_{PC} - \max(\Pi_{3p}, \Pi_R) < F_c$  or  $\Pi_R - \max(\Pi_{3p}, \Pi_{PC}) < F_r$ , where collection or remanufacturing would never be profitable, respectively.  $\square$

**B3. Calculation of Maximum Willingness to Pay.** Recall that in the Stage 1, the subjects only consider new products and in Stage 2, they consider both new and remanufactured products. The steps to calculate the willingness to pay are similar for each case, but for an example, we outline the steps to calculate the willingness to pay for a new product in Stage 2 for a consumer  $i$  and iPod size 16 GB and sold by the OEM. First, regression is carried out to estimate the value of coefficients in equation 7. A piecewise linear function  $b(p)$  is constructed based on the likelihood estimates for an individual evaluated at the

three different price points of \$99, \$149 and \$199. The maximum willingness to pay for the individual is given by  $p$  such that  $p = b^{-1}(\beta_0 + \beta_3 + \beta_4)^3$ .  $\square$

#### **B4. Subsample of Responses to Post-experiment Survey.**

Please share in your own words what you think about the fact that you can buy refurbished Apple electronics?

- a. "I personally do not buy refurbished products [sic] because if they broke once, they will break again.
- b. "I think that refurbished products are not as high quality and more likely to break than new ones."
- c. "I think there are a lot of potential risks involved such as greater potential for getting a flawed iPod or having a shorter iPod lifetime."
- d. "I think that it's a wonderful idea because it is a green product but I don't prefer refurbished products because they always have a glitch."

Why do you think you can buy refurbished Apple electronics (such as iPods)?

- a. "People return products because they do not work."
- b. "There are a high number of returns due to unsatisfied customers."
- c. "In general electronics break or malfunction so instead of throwing them out, why not fix and resell them."
- d. "They probably design them so that they break so that they [sic] can make money off of the same product twice."
- e. "Because they break and Apple fixes them and resells them."
- f. "Refurbs are a great way to turn unused goods into extra profit."
- g. "So that Apple can appear green."
- h. "It costs Apple less to refurbish them than manufacture new products."
- i. "It allows Apple to fix and resell electronics that would otherwise be waste."  $\square$

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<sup>3</sup>If we define the willingness to pay as the price point where the likelihood of purchase is 50% or if we directly use the likelihood scores as a proxy for the willingness to pay, our main conclusions remain unchanged.



## Appendix C

### C1. Proofs

**Proof of Lemma 1.** We will prove this lemma using a proof by contradiction. Suppose the OEM only offers new products in the second period at a list price of  $p_{n2}$  and  $p_{n2} < p_{n1}$ . Thus, there is no difference between the two consumer segments and the OEM's second-period objective function which is concave in  $p_{n2}$  is given by

$$\begin{aligned} \max_{p_{n2}} \Pi_2 &= (p_{n2} - c)(1 - p_{n2}) \\ \text{s.t. } p_{n2} &< p_{n1} \end{aligned}$$

First-order conditions under  $p_{n2} < p_{n1}$  give us that  $p_{n2}^* = \frac{1+c}{2}$  and  $\Pi_2 = \frac{(1-c)^2}{4}$ . We now maximize the OEM's total two-period profit by choosing the list price in the first period  $p_{n1}$  which is given by

$$\max_{p_{n1}} \Pi = (p_{n1} - c)(1 - p_{n1}) + \frac{(1 - c)^2}{4}$$

Solving the first-order conditions gives us  $p_{n1}^* = \frac{1+c}{2}$ . However, this contradicts  $p_{n2} < p_{n1}$  as  $p_{n1}^* = p_{n2}^*$ . Thus, if only new products are offered in the second period, the OEM should always charge a higher list price for the new product in the second period, i.e.  $p_{n1} \leq p_{n2}$ .

**Proof of Proposition 1** We will first begin with the second-period analysis.

*Second Period Analysis:* The OEM's second-period objective function is given by

$$\begin{aligned} \max_{p_{n2}} \Pi_2^{MN}(p_{n1}) &= (1 - p_{n2})(p_{n2} - c) + \int_k^{p_{n2}} (\phi - c - s) d\phi \\ \text{s.t. } k &= \max(p_{n1}, c + s) \end{aligned}$$

The objective function is concave in  $p_{n2}$  and the feasible set is convex because  $p_{n2}$  is constrained in  $[0,1]$ . In addition, we can see from the constraints that  $c + s < 1$ . There are two main scenarios to be analyzed, based on whether  $\max(p_{n1}, c + s) = p_{n1}$  or  $\max(p_{n1}, c + s) = c + s$ .

*Scenario I.*  $c + s \leq p_{n1}$ . Under this case, we have  $k = p_{n1}$  and solving the first-order condition, we get  $p_{n2}^* = 1 - s$  and  $\Pi_2^{MN*}(p_{n1}) = \frac{(1-s)^2 + 2p_{n1}s - 2c(1-p_{n1}) - p_{n1}}{2}$ .

*Scenario II.*  $p_{n1} < c + s$ . Under this case, we have  $k = c + s$  and solving the first-order condition, we get  $p_{n2}^* = 1 - s$  and  $\Pi_2^{MN*} = \frac{(1-c)^2 - s(1-c) + s^2}{2}$ .

*First Period Analysis:* After characterizing the OEM's optimal second-period list price, we now solve for the optimal first-period list price decision. We maximize the total two-period profit  $\Pi^{MN}(p_{n1}) = (1-p_{n1})(p_{n1}-c) + \Pi_2^{MN}(p_{n1})$  to determine  $p_{n1}^{MN*}$  and  $\Pi^{MN*} \doteq \Pi^{MN}(p_{n1}^{MN*})$ . First, we need to check that  $\Pi_2^{MN*}(p_{n1})$  is continuous at the boundary  $p_{n1} = \bar{p} \doteq c + s$ . Since,  $\frac{(1-s)^2 + 2p_{n1}s - 2c(1-p_{n1}) - p_{n1}}{2}$  evaluated at  $\bar{p} \doteq c + s$  is  $\frac{(1-c)^2 - s(1-c) + s^2}{2}$ , this is true. If  $c + s \leq p_{n1}$ , the optimal list price in the first period is given by  $\frac{1+2c+s}{3}$  and if  $p_{n1} < c + s$ , it is given by  $\frac{1+c}{2}$ . At the boundary  $p_{n1} = \bar{p}$ , the derivative of the two-period profit is given by  $1 - c - 2s$ . If this is positive [ $c < 1 - 2s$ ], the optimum is reached at  $c + s \leq p_{n1}^*$ ; if it is negative [ $1 - 2s \leq c$ ], it is reached at  $p_{n1}^* < c + s$ .

We know that the disposal cost is lower than the production cost, i.e.  $s \leq c$ , which implies  $1 - 2s \geq 1 - 2c$ . We can now express the conditions  $c < 1 - 2s$  and  $1 - 2s \leq c$  as  $c < 1/3$  and  $1/3 \leq c$  respectively. Thus, the optimal decisions across the two periods is summarized as follows:

Condition	$p_{n1}^{MN*}$	$p_{n2}^{MN*}$	$\Pi^{MN*}$
$c < 1/3$	$\frac{1+2c+s}{3}$	$1 - s$	$\frac{(2-2c-s)^2}{6} + \frac{s^2}{2}$
$1/3 \leq c$	$\frac{1+c}{2}$	$1 - s$	$\frac{(1-c)^2}{2} + \frac{(1-c-2s)^2}{4}$

Recall that the OEM's profit without price discrimination and when only new products are offered is given by  $\frac{(1-c)^2}{2}$ . If  $c < 1/3$ ,  $\Pi^{MN*} - \Pi^{NN*} = \frac{(1-c-2s)^2}{6} \geq 0$ ; and if  $1/3 \leq c$ , we have  $\Pi^{MN*} - \Pi^{NN*} = \frac{(1-c-2s)^2}{4} \geq 0$ . Thus, in a monopoly market with no competition from remanufactured products, the OEM is no worse off offering a trade-in rebate program even when disposal of traded in units is costly.

**Proof of Proposition 2.** Recall that the set of constraints for the case MR when the OEM offers new and remanufactured products simultaneously and chooses to price discriminate

by offering trade-ins to the  $\alpha$  segment, is given by

$$p_{n2} - p_r \leq 1 - \delta \quad \Rightarrow \quad p_{n2} \leq 1 - \delta + p_r \quad (31)$$

$$p_{n2} - \frac{p_r}{\delta} \geq 0 \quad \Rightarrow \quad \delta p_r \leq p_{n2} \quad (32)$$

$$(1 - \alpha) \frac{(\delta p_{n2} - p_r)}{\delta(1 - \delta)} \leq \alpha(p_{n2} - k) \quad (33)$$

$$k \doteq \max(p_{n1}, c + s) \leq p_{n2} \quad (34)$$

**Lemma 2** *In the optimal solution,  $\delta p_1 \leq p_r$  always holds true.*

We will show this by using a proof by contradiction. Suppose that  $p_r < \delta p_{n1}$  and since we have  $p_r \leq \delta p_{n2}$ , we get  $\delta p_{n2} < \delta p_{n1}$  which can be simplified to  $p_{n2} < p_{n1}$ . This contradicts the constraint  $p_{n1} \leq p_{n2}$  and thus, we should always have  $\delta p_{n1} \leq p_r$ .

Now we can summarize the OEM's second-period problem as follows:

$$\begin{aligned} \max_{p_{n2}, p_r} \Pi_2^{MR} = & \alpha \left[ (1 - p_{n2})(p_{n2} - c) + \int_k^{p_{n2}} (\phi - c - s) d\phi \right] \\ & + (1 - \alpha) \left[ \left( 1 - \frac{p_{n2} - p_r}{1 - \delta} \right) (p_{n2} - c) + \frac{(\delta p_{n2} - p_r)}{\delta(1 - \delta)} (p_r - c_r) + \int_{\frac{p_r}{\delta}}^{\frac{p_{n2} - p_r}{1 - \delta}} s d\phi \right] \end{aligned} \quad (35)$$

$$\delta p_{n1} \leq p_r \quad (36)$$

$$p_r \leq \delta p_{n2} \quad (37)$$

$$k \doteq \max(p_{n1}, c + s) \leq p_{n2} \quad (38)$$

$$p_{n2} \leq 1 - \delta + p_r \quad (39)$$

$$(1 - \alpha) \frac{(\delta p_{n2} - p_r)}{\delta(1 - \delta)} \leq \alpha(p_{n2} - k) \quad (40)$$

It is easy to show that  $\frac{\partial^2 \Pi^{MR}}{\partial p_{n2}^2} = -\frac{2 - \alpha - \alpha\delta}{1 - \delta} < 0$  and  $\frac{\partial^2 \Pi^{MR}}{\partial p_r^2} = -\frac{2(1 - \alpha)}{(1 - \delta)\delta} < 0$ . Given that  $\frac{\partial^2 \Pi^{MR}}{\partial p_{n2} \partial p_r} = \frac{2(1 - \alpha)}{1 - \delta}$ , the determinant of the Hessian is  $\frac{\partial^2 \Pi^{MR}}{\partial p_{n2}^2} \left( \frac{\partial^2 \Pi^{MR}}{\partial p_r^2} \right) - \left( \frac{\partial^2 \Pi^{MR}}{\partial p_{n2} \partial p_r} \right)^2 = \frac{2(2 - \alpha)(1 - \alpha)}{\delta(1 - \delta)} > 0$ . Thus, the objective function is jointly concave in  $p_{n2}$  and  $p_r$ . The set of constraints is convex because both variables  $p_{n2}$  and  $p_r$  are constrained to be in  $[0, 1]$ , and all the constraints of the problem are linear combinations in the variables. If

$\lambda_i \geq 0 \quad \forall i \in \{1, 2, 3, 4, 5\}$ , the Lagrangian function is given by

$$\begin{aligned} \mathbb{L}(p_{n2}, p_r, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5) = & \alpha \left[ (1 - p_{n2})(p_{n2} - c) + \int_k^{p_{n2}} (\phi - c - s) d\phi \right] \\ & + (1 - \alpha) \left[ \left( 1 - \frac{p_{n2} - p_r}{1 - \delta} \right) (p_{n2} - c) + \frac{(\delta p_{n2} - p_r)}{\delta(1 - \delta)} (p_r - c_r) + \int_{\frac{p_r}{\delta}}^{\frac{p_{n2} - p_r}{1 - \delta}} s d\phi \right] - \lambda_1(\delta p_{n1} - p_r) \\ & - \lambda_2(p_r - \delta p_{n2}) - \lambda_3(p_{n1} - p_{n2}) - \lambda_4(p_{n2} - 1 + \delta - p_r) \\ & - \lambda_5 \left( (1 - \alpha) \frac{(\delta p_{n2} - p_r)}{\delta(1 - \delta)} - \alpha(p_{n2} - k) \right) \quad (41) \end{aligned}$$

Since the profit function is jointly concave in the decision variables and the feasible region is convex, the KKT conditions are necessary and sufficient for optimality which are given by  $\frac{\partial \mathbb{L}}{\partial p_{n2}} = 0$ ,  $\frac{\partial \mathbb{L}}{\partial p_r} = 0$ ,  $\lambda_1(\delta p_{n1} - p_r) = 0$ ,  $\lambda_2(p_r - \delta p_{n2}) = 0$ ,  $\lambda_3(p_{n1} - p_{n2}) = 0$ ,  $\lambda_4(p_{n2} - 1 + \delta - p_r) = 0$ ,  $\lambda_5 \left( (1 - \alpha) \frac{(\delta p_{n2} - p_r)}{\delta(1 - \delta)} - \alpha(p_{n2} - k) \right) = 0$  and  $\lambda_i \geq 0 \quad \forall i \in \{1, 2, 3, 4, 5\}$ .

Solving  $\frac{\partial \mathbb{L}}{\partial p_{n2}} = 0$  and  $\frac{\partial \mathbb{L}}{\partial p_r} = 0$ , we get

$$\begin{aligned} p_{n2}(\lambda_1, \lambda_3, \lambda_4, \lambda_5) = & \frac{(1 - \alpha s + \lambda_3 - \lambda_4)(1 - \alpha) + c(1 - \alpha)^2 + \lambda_5 \alpha + \delta(\lambda_1 + \lambda_5)(1 - \alpha)}{(2 - \alpha)(1 - \alpha)} \\ p_r(\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5) = & \frac{\delta \lambda_1(2 - \alpha - \alpha \delta) + \lambda_4 \alpha \delta(1 - \delta) + \lambda_5(2 - \alpha + 2\alpha \delta)}{2(2 - \alpha)(1 - \alpha)} - \frac{\delta \lambda_2(1 - \delta)}{2(1 - \alpha)} \\ & + \frac{2\delta \lambda_3 + \delta(2 - \alpha c - 2\alpha s)}{2(2 - \alpha)} + \frac{c_r - s}{2} \end{aligned}$$

Also, recall that

$$\begin{aligned} {}^\alpha q_{n2}(p_{n2}, p_r) &= \alpha [(1 - p_{n2}) + (p_{n2} - k)] = \alpha(1 - k), \\ q_{n2, 1-\alpha}(p_{n2}, p_r) &= (1 - \alpha) \left( 1 - \frac{p_{n2} - p_r}{1 - \delta} \right) \\ q_r(p_{n2}, p_r) &= (1 - \alpha) \frac{\delta p_{n2} - p_r}{\delta(1 - \delta)} \end{aligned}$$

Denote the number of recovered units through the trade-in program by  $\hat{q}(p_{n2}, k) = \alpha(p_{n2} - k)$ . There are two main scenarios to be analyzed based on whether  $\max(p_{n1}, c + s) = p_{n1}$  (*Scenario I*) or  $\max(p_{n1}, c + s) = c + s$  (*Scenario II*).

*Scenario I.* If  $c + s \leq p_{n1}$ , then we have  $k = p_{n1}$  and there are four main groups of cases to be analyzed based on whether the constraints  $p_r \leq \delta p_{n2}$  and  $p_{n2} \leq 1 - \delta + p_r$  are binding or slack.

*Group A:*  $p_r = \delta p_{n2}$  and  $p_{n2} = 1 - \delta + p_r$ , i.e.  $q_{n2,1-\alpha} = 0$  and  $q_r = 0$ .

In this group we have  $q_r = 0$  and (40) is not binding, which implies that  $q_r(p_{n2}, p_r) < \hat{q}(p_{n2}, p_{n1})$  and  $\lambda_5 = 0$ . We have two candidate cases; if  $\delta p_{n1} < p_r = \delta p_{n2}$ , then  $p_{n1} < p_{n2}$  has to hold true and if  $\delta p_{n1} = p_r = \delta p_{n2}$ , then only  $p_{n1} = p_{n2}$  is feasible.

*Case 1*  $\delta p_{n1} < p_r = \delta p_{n2}$  and  $p_{n1} < p_{n2} = 1 - \delta + p_r$ : In this case, (37) & (39) are binding and (36) & (38) are not binding, so we have  $\lambda_1 = \lambda_3 = 0$  and  $\lambda_2, \lambda_4 \geq 0$ . Solving  $p_r = \delta p_{n2}$  and  $p_{n2} = 1 - \delta + p_r$ , we get  $p_{n2} = 1$  and  $p_r = \delta$ . We can now solve  $p_{n2}(0, 0, \lambda_4, 0) = 1$  and  $p_r(0, \lambda_2, 0, \lambda_4, 0) = \delta$  and we get  $\lambda_2 = -\frac{(1-c)(1-\alpha)+\alpha s}{1-\delta} < 0$  and  $\lambda_4 = \frac{(c_r-s)(1-\alpha)+\delta(3-3\alpha-\alpha s)}{\delta(1-\delta)}$ .

However, this contradicts  $\lambda_2 \geq 0$  and this case is ruled out.

*Case 2*  $\delta p_{n1} = p_r = \delta p_{n2}$  and  $p_{n1} = p_{n2} = 1 - \delta + p_r$ : In this case, (36), (37), (38) & (39) are binding, so we have  $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = 0$ . Solving  $p_{n1} = p_r = \delta p_{n2}$  and  $p_{n1} = p_{n2} = 1 - \delta + p_r$ , we get  $p_{n2} = 1$ ,  $p_r = \delta$  and  $p_{n1} = 1$ . However, this contradicts  $p_{n1} < 1$  and this case is ruled out.

*Group B:*  $p_r = \delta p_{n2}$  and  $p_{n2} < 1 - \delta + p_r$ , i.e.  $q_{n2,1-\alpha} > 0$  and  $q_r = 0$ .

In this group we have  $q_r = 0$  and (40) is not binding, which implies that  $q_r(p_{n2}, p_r) < \hat{q}(p_{n2}, p_{n1})$  and  $\lambda_5 = 0$ . We have two candidate solutions; if  $\delta p_{n1} < p_r = \delta p_{n2}$ , then  $p_{n1} < p_{n2}$  has to hold true and if  $\delta p_{n1} = p_r = \delta p_{n2}$ , then  $p_{n1} = p_{n2}$ .

*Case 3*  $\delta p_{n1} < p_r = \delta p_{n2}$  and  $p_{n1} < p_{n2} < 1 - \delta + p_r$ : In this case, (36), (38) & (39) are not binding and (37) is binding, so we have  $\lambda_1 = \lambda_3 = \lambda_4 = 0$  and  $\lambda_2 \geq 0$ . The optimal value of list price is given by  $p_{n2} = \frac{(1-\alpha s)+c(1-\alpha)}{2-\alpha}$  and by solving  $p_r(0, \lambda_2, 0, 0, 0) = \delta p_{n2}(0, 0, 0, 0)$  we get  $\lambda_2 = \frac{(c_r-s-\delta c)(1-\alpha)}{\delta(1-\delta)}$ . The conditions  $p_{n1} < p_{n2}$  and  $\lambda_2 \geq 0$  can be simplified to  $p_{n1} < \frac{(1-\alpha s)+c(1-\alpha)}{2-\alpha}$  and  $c \leq c_1$  respectively, where  $c_1 = \frac{c_r-s}{\delta}$ . Also, the conditions  $p_{n2} < 1 - \delta + p_r$  and  $q_r(p_{n2}, p_r) < \hat{q}(p_{n2}, p_{n1})$  give us  $c < 1 + \frac{\alpha s}{1-\alpha}$  (which is always true) and  $p_{n1} < \frac{(1-\alpha s)+c(1-\alpha)}{2-\alpha}$  respectively.

*Case 4*  $\delta p_{n1} = p_r = \delta p_{n2}$  and  $p_{n1} = p_{n2} < 1 - \delta + p_r$ : In this case, (39) is not binding and (36), (37) & (38) are binding, so we have  $\lambda_4 = \lambda_1 = 0$  and  $\lambda_2, \lambda_3 \geq 0$ . In this case, we

have  $p_r = \delta p_{n1}$ ,  $p_{n1} = p_{n2}$  and solving  $p_{n2}(0, \lambda_3, 0, 0) = p_{n1}$  and  $p_r(0, \lambda_2, \lambda_3, 0, 0) = \delta p_{n1}$ , we get  $\lambda_2 = c_r - s - \delta c$  and  $\lambda_3 = -(1 - \alpha s) - c(1 - \alpha) + p_{n1}(2 - \alpha)$ . The conditions  $\lambda_2, \lambda_3 \geq 0$  are given by  $c \leq c_1$  and  $\frac{(1-\alpha s)+c(1-\alpha)}{2-\alpha} \leq p_{n1}$  respectively. Condition  $p_{n2} < 1 - \delta + p_r$  can be simplified as  $-(1 - \delta)(1 - p_{n1}) < 0$  which always holds true.

*Group C:*  $p_r < \delta p_{n2}$  and  $p_{n2} < 1 - \delta + p_r$ , i.e.  $q_{n2,1-\alpha} > 0$  and  $q_r > 0$ .

In this group, since  $\delta p_{n1} \leq p_r$  we always have  $p_{n1} < p_{n2}$ . We have four candidate solutions which are as follows:

*Case 5a*  $\delta p_{n1} < p_r < \delta p_{n2}$ ,  $p_{n1} < p_{n2} < 1 - \delta + p_r$  and  $q_r(p_{n2}, p_r) < \hat{q}(p_{n2}, p_{n1})$ : In this case, (36), (37), (38), (39) & (40) are not binding, so we have  $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = 0$ . The optimal prices are given by  $p_{n2} = p_{n2}(0, 0, 0, 0) = \frac{1-\alpha s+c(1-\alpha)}{2-\alpha}$  and  $p_r = p_r(0, 0, 0, 0, 0) = \frac{(c_r-s)(2-\alpha)+2\delta(1-\alpha s)-\alpha\delta c}{2(2-\alpha)}$ . The conditions  $\delta p_{n1} < p_r$ ,  $p_{n1} < p_{n2}$ ,  $p_r < \delta p_{n2}$ ,  $p_{n2} < 1 - \delta + p_r$  and  $q_r(p_{n2}, p_r) < \hat{q}(p_{n2}, p_{n1})$  are given by  $p_{n1} \leq \frac{(c_r-s)(2-\alpha)+2\delta(1-\alpha s)-\alpha\delta c}{2\delta(2-\alpha)}$ ,  $p_{n1} < \frac{(1-\alpha s)+c(1-\alpha)}{2-\alpha}$ ,  $c_1 \leq c$ ,  $c < c_2 \doteq \frac{c_r(2-\alpha)+2(1-s)(1+\alpha\delta)+3\alpha s-2\alpha-2\delta}{2-2\alpha+\alpha\delta}$  and  $p_{n1} < \frac{(c_r+s)(1-\alpha)(2-\alpha)-2\delta(1-\alpha s)(2-3\alpha+\alpha\delta)-\delta c(1-\alpha)(2-5\alpha+2\alpha\delta)}{2\alpha\delta(2-\alpha)(1-\delta)}$  respectively.

*Case 5b*  $\delta p_{n1} < p_r < \delta p_{n2}$ ,  $p_{n1} < p_{n2} < 1 - \delta + p_r$  and  $q_r(p_{n2}, p_r) = \hat{q}(p_{n2}, p_{n1})$ : In this case, (40) is binding and (36), (37), (38) & (39) are not binding, so we have  $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = 0$  and  $\lambda_5 \geq 0$ . If we solve  $q_r(p_{n2}, p_r) = \hat{q}(p_{n2}, p_{n1})$ ,  $p_{n2}(0, 0, 0, \lambda_5) = p_{n2}$  and  $p_r(0, 0, 0, 0, \lambda_5) = p_r$ , we get  $p_{n2} = \frac{(1-\alpha)(1-\alpha c_r)+c(1-\alpha)(1-\alpha+\alpha\delta)+2\alpha^2\delta(1-\delta)p_{n1}}{(2-\alpha)(1-\alpha)+2\alpha^2\delta(1-\delta)}$ ,  $p_r = \frac{\delta(1-2\alpha+\alpha\delta)((c-c_r)(1-\alpha)+(1-\delta)+s(1-2\alpha+\alpha\delta)+\delta p_{n1}(2\delta+\alpha(2-\alpha)(1-4\delta+\delta^2)))}{(1-\alpha)(2-\alpha-\alpha\delta)}$  and  $\lambda_5 = 2\alpha\delta(1-\delta)(2-\alpha)p_{n1} - (c_r-s)(2-\alpha)(1-\alpha)+\delta c(1-\alpha)(2-3\alpha+2\alpha\delta)-2\alpha\delta(1-\delta)(1+\alpha s)+4s$ . The conditions  $\lambda_5 \geq 0$  &  $q_r(p_{n2}, p_r) < \hat{q}(\cdot)$  are given by  $\frac{(c_r+s)(2-\alpha)(1-\alpha)-\delta c(1-\alpha)(2-3\alpha+2\alpha\delta)+2\alpha\delta(1-\delta)(1+\alpha s)-4s}{2\alpha\delta(1-\delta)(2-\alpha)} \leq p_{n1}$  and  $\frac{(c_r-s)(2-\alpha)(1-\alpha)-2\alpha\delta c_r(1-\alpha)+\alpha\delta c(1-\alpha)+2\delta(1-\alpha\delta)-2\alpha^2\delta s(2-\delta)}{2\delta(1-\alpha)(2-\alpha)} < p_{n1}$  respectively.

*Case 6a*  $\delta p_{n1} = p_r < \delta p_{n2}$ ,  $p_{n1} < p_{n2} < 1 - \delta + p_r$  and  $q_r(p_{n2}, p_r) < \hat{q}(p_{n2}, p_{n1})$ : In this case, (36) is binding and (37), (38), (39) & (40) are not binding, so we have  $\lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = 0$  and  $\lambda_1 \geq 0$ . Solving  $p_{n2}(\lambda_1, 0, 0, 0) = p_{n2}$  and  $p_r(\lambda_1, 0, 0, 0, 0) = \delta p_{n1}$  together we get,  $p_{n2} = \frac{(1-\alpha)(c+s-c_r)+(1-\delta)(1-\alpha s)+2\delta p_{n1}(1-\alpha)}{2-\alpha-\alpha\delta}$  and  $\lambda_1 = -(c_r - s)(2 - \alpha) - \delta(2 - 2p_{n1}(2 - \alpha) - \alpha c - 2\alpha s)$ . The conditions  $p_{n1} < p_{n2}$ ,  $p_r < \delta p_{n2}$ ,  $p_{n2} < 1 - \delta + p_r$  and  $\lambda_1 \geq 0$  are given by  $c < \frac{(c_r-s)(1-\alpha)+(1-\delta)(1-\alpha s)}{1-\alpha}$ ,  $p_{n1} < \frac{(1-\alpha)(c+s-c_r)+(1-\delta)(1-\alpha s)}{(1-\delta)(2-\alpha)}$ ,  $\frac{\delta(1-\alpha\delta)-\alpha s(1-\delta)-(1-\alpha)(1-c+c_r-s)}{\alpha\delta(1-\delta)} < p_{n1}$  and  $\frac{(c_r-s)(2-\alpha)-2\delta(1-\alpha s)+\alpha\delta c}{2\delta(2-\alpha)} \leq p_{n1}$ .

*Case 6b*  $\delta p_{n1} = p_r < \delta p_{n2}$ ,  $p_{n1} < p_{n2} < 1 - \delta + p_r$  and  $q_r(p_{n2}, p_r) = \hat{q}(p_{n2}, p_{n1})$ : In this case (36) & (40) are binding and (37), (38) & (39) are not binding, so we have  $\lambda_2 = \lambda_3 = \lambda_4 = 0$  and  $\lambda_1, \lambda_5 \geq 0$ . Solving  $q_r(p_{n2}, \delta p_{n1}) = \hat{q}(p_{n2}, p_{n1})$ , we get  $p_{n2} = p_{n1}$  which contradicts  $p_{n1} < p_{n2}$  and this case is ruled out.

*Group D:*  $p_r < \delta p_{n2}$  and  $p_{n2} = 1 - \delta + p_r$ , i.e.  $q_{n2,1-\alpha} = 0$  and  $q_r > 0$ .

In this group, since  $\delta p_{n1} \leq p_r$  we always have  $p_{n1} < p_{n2}$ . We have four candidate solutions which are as follows:

*Case 7a*  $\delta p_{n1} < p_r < \delta p_{n2}$ ,  $p_{n1} < p_{n2} = 1 - \delta + p_r$  and  $q_r(p_{n2}, p_r) < \hat{q}(p_{n2}, p_{n1})$ : In this case, (39) is binding and (36), (37), (38) & (40) are not binding, so we have  $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_5 = 0$  and  $\lambda_4 \geq 0$ . Solving  $p_{n2}(0, 0, \lambda_4, 0) = 1 - \delta + p_r(0, 0, 0, \lambda_4, 0)$  and  $p_r(0, 0, 0, \lambda_4, 0) = p_r$  together, we get  $p_r = \frac{(1-\alpha)(c_r-s+\delta)+\alpha\delta(\delta-s)}{2-2\alpha+\alpha\delta}$  and  $\lambda_4 = c(2-2\alpha+\alpha\delta) - 2\alpha\delta(1-s) - 2(1-s-\alpha-\delta) - 3\alpha s - c_r(2-\alpha)$ . The conditions  $\delta p_{n1} < p_r$ ,  $p_{n1} < p_{n2}$ ,  $q_r(p_{n2}, p_r) < \hat{q}(p_{n2}, p_{n1})$  and  $\lambda_4 \geq 0$  are given by  $p_{n1} < \frac{(1-\alpha)(c_r-s+\delta)+\alpha\delta(\delta-s)}{\delta(2-2\alpha+\alpha\delta)}$ ,  $p_{n1} < \frac{(1-\alpha)(2+c_r-s)-\delta(1-2\alpha+\alpha s)}{2-2\alpha+\alpha\delta}$ ,  $p_{n1} < \frac{(c_r-s)(1-\alpha)^2+\alpha^2\delta^2(1-s)-\delta(1-\alpha)(1-\alpha c_r)+\alpha\delta(1-\alpha)(3-2s-\delta)}{\alpha\delta(2-2\alpha+\alpha\delta)}$  and  $c_2 \leq c$ .

*Case 7b*  $\delta p_{n1} < p_r < \delta p_{n2}$ ,  $p_{n1} < p_{n2} = 1 - \delta + p_r$  and  $q_r(p_{n2}, p_r) = \hat{q}(p_{n2}, p_{n1})$ : In this case, (39) & (40) is binding and (36), (37) & (38) are not binding, so we have  $\lambda_1 = \lambda_2 = \lambda_3 = 0$  and  $\lambda_4, \lambda_5 \geq 0$ . If we solve  $q_r = \hat{q}(p_{n2}, p_{n1})$  and  $p_{n2} = 1 - \delta + p_r$  we get  $p_{n2} = \frac{1-\alpha+\alpha\delta p_{n1}}{1-\alpha+\alpha\delta}$  and  $p_r = \frac{\delta-2\alpha\delta+\alpha\delta p_{n1}+\alpha\delta}{1-\alpha+\alpha\delta}$ . By solving  $p_{n2}(0, 0, \lambda_4, \lambda_5) = \frac{1-\alpha+\alpha\delta p_{n1}}{1-\alpha+\alpha\delta}$  and  $p_r(0, 0, 0, \lambda_4, \lambda_5) = \frac{\delta-2\alpha\delta+\alpha\delta p_{n1}+\alpha\delta}{1-\alpha+\alpha\delta}$  together, we get  $\lambda_4 = -1 + c(1+\alpha(1-\delta))^2 - \alpha(-2+c_r+\alpha-c_r\alpha+(-1+p_{n1}(2-3\alpha)+\alpha(2+c_r))\delta-2\alpha\delta^2(1-p_{n1}))$  and  $\lambda_5 = \alpha\delta(2-2\alpha+\alpha\delta)p_{n1} - (c_r-s)(1-\alpha)^2 - \alpha^2\delta^2(1-s) + \delta(1-\alpha)(1-\alpha c_r) - \alpha\delta(1-\alpha)(3-2s-\delta)$ . The condition  $\lambda_5 \geq 0$  gives us  $\frac{(c_r-s)(1-\alpha)^2+\alpha^2\delta^2(1-s)-\delta(1-\alpha)(1-\alpha c_r)+\alpha\delta(1-\alpha)(3-2s-\delta)}{\alpha\delta(2-2\alpha+\alpha\delta)} \leq p_{n1}$ .

*Case 8a*  $\delta p_{n1} = p_r < \delta p_{n2}$ ,  $p_{n1} < p_{n2} = 1 - \delta + p_r$  and  $q_r(p_{n2}, p_r) < \hat{q}(p_{n2}, p_{n1})$ : In this case, (36) & (39) are binding and (37), (38) & (40) are not binding, so we have  $\lambda_2 = \lambda_3 = \lambda_5 = 0$  and  $\lambda_1, \lambda_4 \geq 0$ . In this case, we have  $p_r = \delta p_{n1}$ ,  $p_{n2} = 1 - \delta + p_r = 1 - \delta + \delta p_{n1}$  and solving  $p_{n2}(\lambda_1, 0, \lambda_4, 0) = 1 - \delta + \delta p_{n1}$  and  $p_r(\lambda_1, 0, 0, \lambda_4, 0) = \delta p_{n1}$ , we get  $\lambda_1 = (1-\alpha)(s-c_r-\delta) + \delta p_{n1}(2-2\alpha+\alpha\delta) + \alpha\delta(s-\delta)$  and  $\lambda_4 = \delta(1-\alpha\delta) - \alpha s(1-\delta) - (1-\alpha)(1-c+c_r-s) - \alpha\delta(1-\delta)p_{n1}$ . The conditions  $\lambda_1, \lambda_4 \geq 0$  give us  $\frac{(1-\alpha)(c_r-s+\delta)+\alpha\delta(\delta-s)}{\delta(2-2\alpha+\alpha\delta)} \leq p_{n1}$  and  $p_{n1} \leq \frac{\delta(1-\alpha\delta)-\alpha s(1-\delta)-(1-\alpha)(1-c+c_r-s)}{\alpha\delta(1-\delta)}$ . Simplifying these two conditions together, we

get  $c_2 \leq c$ . Also, both  $p_r < \delta p_{n2}$  and  $p_{n1} < p_{n2}$  simplify to  $-(1-\delta)(1-p_{n1}) < 0$  which always holds true.

*Case 8b*  $\delta p_{n1} = p_r < \delta p_{n2}$ ,  $p_{n1} < p_{n2} = 1 - \delta + p_r$  and  $q_r(p_{n2}, p_r) = \hat{q}(p_{n2}, p_{n1})$ : In this case (36) & (39) are binding and (37), (38) & (40) are not binding, so we have  $\lambda_2 = \lambda_3 = \lambda_5 = 0$  and  $\lambda_1, \lambda_4 \geq 0$ . Solving  $p_r = \delta p_{n1}$ ,  $p_{n2} = 1 - \delta + \delta p_{n1}$  and  $q_r = \hat{q}(p_{n2}, p_{n1})$ , we get  $p_{n1} = 1$ ,  $p_{n2} = 1$  and  $p_r = \delta$ . However, since we need  $p_{n1} < 1$ , this cannot hold and is ruled out.

*Scenario II.* If  $p_{n1} < c + s$ , then we have  $k = c + s$  and there are four main groups of cases to be analyzed, depending on whether the constraints  $p_r \leq \delta p_{n2}$  and  $p_{n2} \leq 1 - \delta + p_r$  are binding or slack.

*Group A:*  $p_r = \delta p_{n2}$  and  $p_{n2} = 1 - \delta + p_r$ , i.e.  $q_{n2,1-\alpha} = 0$  and  $q_r = 0$ .

In this group we have  $q_r = 0$  and (40) is not binding, which implies that  $q_r(p_{n2}, p_r) < \hat{q}(p_{n2}, c + s)$  and  $\lambda_5 = 0$ . Note that we cannot have  $\delta p_{n1} = p_r$  since it implies  $p_{n1} = p_{n2}$ . We also require  $c + s \leq p_{n2}$  which gives us  $c + s \leq p_{n1}$  and contradicts the defining condition. We have two candidate cases; 1).  $\delta p_{n1} < p_r = \delta p_{n2}$  and  $c + s < p_{n2} = 1 - \delta + p_r$  and 2).  $\delta p_{n1} < p_r = \delta p_{n2}$  and  $c + s = p_{n2} = 1 - \delta + p_r$ .

*Case 9*  $\delta p_{n1} < p_r = \delta p_{n2}$  and  $c + s < p_{n2} = 1 - \delta + p_r$ : In this case, (37) & (39) are binding and (36) & (38) are not binding, so we have  $\lambda_1 = \lambda_3 = 0$  and  $\lambda_2, \lambda_4 \geq 0$ . Solving  $p_r = \delta p_{n2}$  and  $p_{n2} = 1 - \delta + p_r$ , we get  $p_{n2} = 1$  and  $p_r = \delta$ . We can now solve  $p_{n2}(0, 0, \lambda_4, 0) = 1$  and  $p_r(0, \lambda_2, 0, \lambda_4, 0) = \delta$  and we have  $\lambda_2 = -\frac{(1-c)(1-\alpha)+\alpha s}{1-\delta} < 0$  and  $\lambda_4 = \frac{(c_r-s)(1-\alpha)+\alpha\delta(1-s)-\delta}{\delta(1-\delta)}$ . However, this contradicts  $\lambda_2 \geq 0$  and this case is ruled out.

*Case 10*  $\delta p_{n1} < p_r = \delta p_{n2}$  and  $c + s = p_{n2} = 1 - \delta + p_r$ : In this case, (37), (38) & (39) are binding, so we have  $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = 0$ . Thus, we have  $p_r = \delta(c + s)$  and  $p_{n2} = c + s$  and  $p_{n2} = 1 - \delta + p_r$  requires  $c + s = 1$  which contradicts  $c + s < 1$  and this case is ruled out.

*Group B:*  $p_r = \delta p_{n2}$  and  $p_{n2} < 1 - \delta + p_r$ , i.e.  $q_{n2,1-\alpha} > 0$  and  $q_r = 0$ .

In this group we have  $q_r = 0$  and (40) is not binding, which implies that  $q_r(p_{n2}, p_r) < \hat{q}(p_{n2}, c + s)$  and  $\lambda_5 = 0$ . In this group, we cannot have  $\delta p_{n1} = p_r$  which leads to  $p_{n1} =$



$p_{n2} \geq c + s$  and contradicts  $p_{n1} < c + s$ . Thus, we have two candidate solutions;  $c + s < p_{n2}$  and  $c + s = p_{n2}$ .

*Case 11*  $\delta p_{n1} < p_r = \delta p_{n2}$  and  $c + s < p_{n2} < 1 - \delta + p_r$ : In this case, (36), (38) & (39) are not binding and (37) is binding, so we have  $\lambda_1 = \lambda_3 = \lambda_4 = \lambda_5 = 0$  and  $\lambda_2 \geq 0$ . The optimal value of list price is given by  $p_{n2} = \frac{(1-\alpha s)+c(1-\alpha)}{2-\alpha}$  and by solving  $p_r(0, \lambda_2, 0, 0, 0) = \delta p_{n2}(0, 0, 0, 0)$  we get  $\lambda_2 = \frac{(c_r-s-\delta c)(1-\alpha)}{\delta(1-\delta)}$ . The conditions  $c + s < p_{n2}$  and  $\lambda_2 \geq 0$  can be simplified to  $c < c_0$  and  $c \leq c_1$  respectively. Also, the conditions  $p_{n2} < 1 - \delta + p_r$  and  $q_r(p_{n2}, p_r) < \hat{q}(p_{n2}, c + s)$  give us  $p_{n2} < 1$  (which is always true) and  $c < c_0$  respectively.

*Case 12*  $\delta p_{n1} < p_r = \delta p_{n2}$  and  $c + s = p_{n2} < 1 - \delta + p_r$ : In this case, (39) & (36) are not binding and (37) & (38) are binding, so we have  $\lambda_4 = \lambda_1 = \lambda_5 = 0$  and  $\lambda_2, \lambda_3 \geq 0$ . In this case, we have  $p_r = \delta(c + s)$ ,  $p_{n2} = c + s$  and solving  $p_{n2}(0, \lambda_3, 0, 0) = c + s$  and  $p_r(0, \lambda_2, \lambda_3, 0, 0) = \delta(c + s)$ , we get  $\lambda_2 = c_r - s - \delta c$  and  $\lambda_3 = -1 + c + 2s$ . The conditions  $\lambda_2, \lambda_3 \geq 0$  give us  $c \leq c_1$  and  $c_0 \leq c$  respectively. Condition  $p_{n2} < 1 - \delta + p_r$  can be simplified as  $c + s < 1$  which always holds true.

*Group C:*  $p_r < \delta p_{n2}$  and  $p_{n2} < 1 - \delta + p_r$ , i.e.  $q_{n2,1-\alpha} > 0$  and  $q_r > 0$ .

In this group, we have  $q_r(p_{n2}, p_r) > 0$  and since  $\hat{q}(p_{n2}, c + s) = p_{n2} - c + s$ , we cannot have  $p_{n2} = c + s$  as it leads to  $q_r(p_{n2}, p_r) \leq 0$  which is not feasible. Thus, we have four candidate solutions which are as follows:

*Case 13a*  $\delta p_{n1} < p_r < \delta p_{n2}$ ,  $c + s < p_{n2} < 1 - \delta + p_r$  and  $q_r(p_{n2}, p_r) < \hat{q}(p_{n2}, c + s)$ : In this case, (36), (37), (38), (39) & (40) are not binding, so we have  $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = 0$ . The optimal prices are given by  $p_{n2} = p_{n2}(0, 0, 0, 0) = \frac{1-\alpha s+c(1-\alpha)}{2-\alpha}$  and  $p_r = p_r(0, 0, 0, 0, 0) = \frac{(c_r-s)(2-\alpha)+2\delta(1-\alpha s)-\alpha\delta c}{2(2-\alpha)}$ . The conditions  $\delta p_{n1} < p_r$ ,  $c + s < p_{n2}$ ,  $p_r < \delta p_{n2}$  and  $p_{n2} < 1 - \delta + p_r$  are given by  $\frac{(c_r-s)(2-\alpha)+2\delta(1-\alpha s)-\alpha\delta c}{2(2-\alpha)}$ ,  $c < c_0$ ,  $c_1 < c$  and  $c < c_2$  respectively.

*Case 13b*  $\delta p_{n1} < p_r < \delta p_{n2}$ ,  $c + s < p_{n2} < 1 - \delta + p_r$  and  $q_r(p_{n2}, p_r) = \hat{q}(p_{n2}, c + s)$ : In this case, (40) is binding and (36), (37), (38) & (39) are not binding, so we have  $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = 0$  and  $\lambda_5 \geq 0$ . If we solve  $q_r(p_{n2}, p_r) = \hat{q}(p_{n2}, c + s)$ ,  $p_{n2}(0, 0, 0, \lambda_5) = p_{n2}$  and  $p_r(0, 0, 0, 0, \lambda_5) = p_r$ , we get  $p_{n2} = \frac{(1-\alpha)(1-\alpha c_r)+c(1-\alpha)(1-\alpha+\alpha\delta)+2\alpha^2\delta(1-\delta)p_{n1}}{(2-\alpha)(1-\alpha)+2\alpha^2\delta(1-\delta)}$ ,

$$p_r = \frac{(1-\alpha)(1-2\alpha+\alpha\delta)(c-c_r)-\alpha\delta^2(1-\alpha s)-4\alpha s(1-\alpha)+(1-\delta)+s-2\alpha+p_{n1}(\alpha(2-\delta)(1+\delta^2)+\delta(2-8\alpha-4\alpha^2))}{(1-\alpha)(2-\alpha-\delta)} \& \lambda_5 =$$

$$2\alpha\delta(1-\delta)(2-\alpha)p_{n1}-(c_r-s)(2-\alpha)(1-\alpha)+\delta c(1-\alpha)(2-3\alpha+2\alpha\delta)-2\alpha\delta(1-\delta)(1+\alpha s)+4s.$$

$$\text{The conditions } \lambda_5 \geq 0 \text{ is given by } \frac{(c_r+s)(2-\alpha)(1-\alpha)-\delta c(1-\alpha)(2-3\alpha+2\alpha\delta)+2\alpha\delta(1-\delta)(1+\alpha s)-4s}{2\alpha\delta(1-\delta)(2-\alpha)} \leq p_{n1}.$$

*Case 14a*  $\delta p_{n1} = p_r < \delta p_{n2}$ ,  $c + s < p_{n2} < 1 - \delta + p_r$  and  $q_r(p_{n2}, p_r) < \hat{q}(p_{n2}, c + s)$ :

In this case, (36) is binding and (37), (38), (39) & (40) are not binding, so we have  $\lambda_2 =$

$\lambda_3 = \lambda_4 = \lambda_5 = 0$  and  $\lambda_1 \geq 0$ . Solving  $p_{n2}(\lambda_1, 0, 0, 0) = p_{n2}$  and  $p_r(\lambda_1, 0, 0, 0, 0) = \delta p_{n1}$

together we get,  $p_{n2} = \frac{(1-\alpha)(c+s-c_r)+(1-\delta)(1-\alpha s)+2\delta p_{n1}(1-\alpha)}{2-\alpha-\alpha\delta}$  and  $\lambda_1 = -(c_r - s)(2 - \alpha) -$

$\delta(2 - 2p_{n1}(2 - \alpha) - \alpha c - 2\alpha s)$ . The conditions  $p_{n1} < p_{n2}$ ,  $c + s < p_{n2}$ ,  $p_{n2} < 1 - \delta +$

$p_r$ ,  $\lambda_1 \geq 0$  and  $q_r(p_{n2}, p_r) < \hat{q}(p_{n2}, c + s)$  are given by  $p_{n1} < \frac{(c-c_r+s)(1-\alpha)+(1-\alpha s)(1-\delta)}{(2-\alpha)(1-\delta)}$ ,

$\frac{(1-\alpha\delta)(c+s)+c_r(1-\alpha)-(1-\delta)(1-\alpha s)}{2\delta(1-\alpha)} < p_{n1}$ ,  $\frac{(1-\alpha)(c-c_r+s)-(1-\delta)(1+\alpha s-\alpha\delta\alpha)}{\alpha\delta(1-\alpha)} < p_{n1}$  and

$$\frac{-(c_r-s)(1-\alpha)(1-2\alpha+\alpha\delta)+(1-\alpha)(1+c)(1-\delta)-\alpha(1-\delta)(1-\alpha s)(1-\delta-s)+\alpha c(1-\delta)(1-\alpha\delta)}{(1-\alpha)(1-\delta)(2-\alpha+2\alpha\delta)} \leq p_{n1}.$$

*Case 14b*  $\delta p_{n1} = p_r < \delta p_{n2}$ ,  $c + s < p_{n2} < 1 - \delta + p_r$  and  $q_r(p_{n2}, p_r) = \hat{q}(p_{n2}, c + s)$ :

In this case (36) & (40) are binding and (37), (38) & (39) are not binding, so we have

$\lambda_2 = \lambda_3 = \lambda_4 = 0$  and  $\lambda_1, \lambda_5 \geq 0$ . Solving  $q_r(p_{n2}, \delta p_{n1}) = \hat{q}(p_{n2}, c + s)$  and  $p_r = \delta p_{n1}$ ,

we get  $p_{n2} = \frac{p_{n1}(1-\alpha)-\alpha(1-\delta)(c+s)}{1-2\alpha+\alpha\delta}$ . We can now solve  $p_{n2}(\lambda_1, 0, 0, \lambda_5) = \frac{p_{n1}(1-\alpha)-\alpha(1-\delta)(c+s)}{1-2\alpha+\alpha\delta}$

and  $p_r(\lambda_1, 0, 0, 0, \lambda_5) = \delta p_{n1}$  to get  $\lambda_1 = p_{n1}((2 - \alpha)(1 - \alpha) + 2\alpha^2\delta(1 - \delta)) - \alpha s(1 - \alpha)(1 -$

$\delta) - (1 - \alpha)(1 + c) + \alpha(1 - s)(1 - \delta) - \alpha^2 c(1 - \delta^2) - 2\alpha^2 \delta s(1 - \delta) + \alpha c_r(1 - 2\alpha + \alpha\delta)$

and  $\lambda_5 = c(1 - \alpha + \alpha^2 - \alpha\delta - \alpha^2\delta(1 - \delta)) + (1 - \delta) - \alpha(2 - 3\delta + \alpha\delta) - c_r(1 - \alpha)(1 -$

$2\alpha + \alpha\delta) + s(1 - 2\alpha - 3\alpha^2 - 4\alpha^2\delta + 2\alpha^2\delta^2) - p_{n1}(1 - \alpha)(1 - \delta)(2 - \alpha + 2\alpha\delta)$ . The

conditions  $p_r < \delta p_{n2}$ ,  $c + s < p_{n2}$ ,  $\lambda_1 \geq 0$  and  $\lambda_5 \geq 0$  are given by  $\frac{c+s-p_{n1}}{1-2\alpha+\alpha\delta} < 0$ ,

$$\frac{c+s-p_{n1}}{1-2\alpha+\alpha\delta} < 0, \quad \frac{\alpha s(1-\alpha)(1-\delta)+(1-\alpha)(1+c)-\alpha(1-s)(1-\delta)+\alpha^2 c(1-\delta^2)+2\alpha^2 \delta s(1-\delta)-\alpha c_r(1-2\alpha+\alpha\delta)}{(2-\alpha)(1-\alpha)+2\alpha^2 \delta(1-\delta)} \leq p_{n1}$$

$$\text{and } p_{n1} \leq \frac{c(1-\alpha+\alpha^2-\alpha\delta-\alpha^2\delta(1-\delta))+(1-\delta)-\alpha(2-3\delta+\alpha\delta)-c_r(1-\alpha)(1-2\alpha+\alpha\delta)+s(1-2\alpha-3\alpha^2-4\alpha^2\delta+2\alpha^2\delta^2)}{(1-\alpha)(1-\delta)(2-\alpha+2\alpha\delta)}.$$

*Group D:*  $p_r < \delta p_{n2}$  and  $p_{n2} = 1 - \delta + p_r$ , i.e.  $q_{n2,1-\alpha} = 0$  and  $q_r > 0$ .

In this group, we have  $q_r(p_{n2}, p_r) > 0$  and since  $\hat{q}(p_{n2}, c + s) = p_{n2} - c + s$ , we cannot have

$p_{n2} = c + s$  as it leads to  $q_r(p_{n2}, p_r) \leq 0$  which is not feasible. Thus, we have three candidate

solutions which are as follows:

*Case 15a*  $\delta p_{n1} < p_r < \delta p_{n2}$ ,  $c + s < p_{n2} = 1 - \delta + p_r$  and  $q_r(p_{n2}, p_r) < \hat{q}(p_{n2}, c + s)$ : In this

case, (39) is binding and (36), (37), (38) & (40) are not binding, so we have  $\lambda_1 = \lambda_2 = \lambda_3 =$

$\lambda_5 = 0$  and  $\lambda_4 \geq 0$ . Solving  $p_{n2}(0, 0, \lambda_4, 0) = 1 - \delta + p_r(0, 0, 0, \lambda_4, 0)$  and  $p_r(0, 0, 0, \lambda_4, 0) = p_r$

together, we get  $p_r = \frac{(1-\alpha)(c_r-s+\delta)+\alpha\delta(\delta-s)}{2-2\alpha+\alpha\delta}$ ,  $p_{n2} = \frac{(1-\alpha)(2+c_r-s)-\delta(1-2\alpha+\alpha s)}{2(1-\alpha)+\alpha\delta}$  and  $\lambda_4 = c(2 - 2\alpha + \alpha\delta) - 2\alpha\delta(1-s) - 2(1-s-\alpha-\delta) - 3\alpha s - c_r(2-\alpha)$ . The conditions  $\delta p_{n1} < p_r$ ,  $c+s < p_{n2}$ ,  $q_r(p_{n2}, p_r) < \hat{q}(p_{n2}, c+s)$  and  $\lambda_4 \geq 0$  are given by  $p_{n1} < \frac{(1-\alpha)(c_r-s+\delta)+\alpha\delta(\delta-s)}{\delta(2-2\alpha+\alpha\delta)}$ ,  $c < \frac{(1-\alpha)(c_r-3s+2-\delta)+\alpha\delta(1-2s)}{2-2\alpha+\alpha\delta}$ ,  $c < \frac{(c_r-s)(1-\alpha)^2-\delta(1-\alpha)(1-3\alpha-\alpha c_r+4\alpha s)-\alpha\delta^2+2\alpha^2\delta^2(1-s)}{\alpha\delta(2(1-\alpha)+\alpha\delta)}$  &  $c_2 \leq c$ .

*Case 15b*  $\delta p_{n1} < p_r < \delta p_{n2}$ ,  $c+s < p_{n2} = 1-\delta+p_r$  and  $q_r(p_{n2}, p_r) = \hat{q}(p_{n2}, c+s)$ : In this case, (39) & (40) is binding and (36), (37) & (38) are not binding, so we have  $\lambda_1 = \lambda_2 = \lambda_3 = 0$  and  $\lambda_4, \lambda_5 \geq 0$ . If we solve  $q_r = \hat{q}(p_{n2}, c+s)$  and  $p_{n2} = 1-\delta+p_r$  we get  $p_{n2} = \frac{1-\alpha+\alpha\delta^2(c+s)}{(1-\alpha)(1+\delta)+\alpha\delta^2}$  and  $p_r = \frac{\delta(1-2\alpha+\alpha\delta)+\alpha\delta(c+s)}{(1-\alpha)(1+\delta)+\alpha\delta^2}$ . By solving  $p_{n2}(0, 0, \lambda_4, \lambda_5) = \frac{1-\alpha+\alpha\delta^2(c+s)}{(1-\alpha)(1+\delta)+\alpha\delta^2}$  and  $p_r(0, 0, 0, \lambda_4, \lambda_5) = \frac{\delta(1-2\alpha+\alpha\delta)+\alpha\delta(c+s)}{(1-\alpha)(1+\delta)+\alpha\delta^2}$  together, we get  $\lambda_4 = c((1-\alpha)(1-\alpha+\delta) + \alpha^2\delta(1-\delta)(2+\delta)) - (1-\alpha)^2 + \delta(1-\alpha) - 2\alpha^2\delta(1-s) + \alpha^2\delta^2(2+s) - c_r(\alpha(1-\alpha) + \alpha\delta(1-\alpha+\alpha\delta))$  and  $\lambda_5 = -(c_r-s)(1-\alpha)^2 + \delta(1-\alpha)(1-3\alpha-\alpha c_r+4\alpha s) + \alpha\delta^2 - 2\alpha^2\delta^2(1-s) + c(\alpha\delta(2(1-\alpha) + \alpha\delta))$ . The conditions  $\lambda_4 \geq 0$  and  $\lambda_5 \geq 0$  are given by  $\frac{(1-\alpha)^2-\delta(1-\alpha)+2\alpha^2\delta(1-s)-\alpha^2\delta^2(2+s)+c_r(\alpha(1-\alpha)+\alpha\delta(1-\alpha+\alpha\delta))}{(1-\alpha)(1-\alpha+\delta)+\alpha^2\delta(1-\delta)(2+\delta)} \leq c$  and  $\frac{(c_r-s)(1-\alpha)^2-\delta(1-\alpha)(1-3\alpha-\alpha c_r+4\alpha s)-\alpha\delta^2+2\alpha^2\delta^2(1-s)}{\alpha\delta(2(1-\alpha)+\alpha\delta)} \leq c$ .

*Case 16*  $\delta p_{n1} = p_r < \delta p_{n2}$ ,  $c+s < p_{n2} = 1-\delta+p_r$  and  $q_r(p_{n2}, p_r) < \hat{q}(p_{n2}, c+s)$ : In this case, (36) & (39) are binding and (37), (38) & (40) are not binding, so we have  $\lambda_2 = \lambda_3 = \lambda_5 = 0$  and  $\lambda_1, \lambda_4 \geq 0$ . In this case, we have  $p_r = \delta p_{n1}$ ,  $p_{n2} = 1-\delta+p_r = 1-\delta+\delta p_{n1}$  and solving  $p_{n2}(\lambda_1, 0, \lambda_4, 0) = 1-\delta+\delta p_{n1}$  and  $p_r(\lambda_1, 0, 0, \lambda_4, 0) = \delta p_{n1}$ , we get  $\lambda_1 = (1-\alpha)(s-c_r-\delta) + \delta p_{n1}(2-2\alpha+\alpha\delta) + \alpha\delta(s-\delta)$  and  $\lambda_4 = \delta(1-\alpha\delta) - \alpha s(1-\delta) - (1-\alpha)\alpha(1-c+c_r-s) - \alpha\delta(1-\delta)p_{n1}$ . The conditions  $\lambda_1, \lambda_4 \geq 0$  give us  $\frac{(1-\alpha)(c_r-s+\delta)+\alpha\delta(\delta-s)}{\delta(2-2\alpha+\alpha\delta)} \leq p_{n1}$  and  $p_{n1} \leq \frac{\delta(1-\alpha\delta)-\alpha s(1-\delta)-(1-\alpha)(1-c+c_r-s)}{\alpha\delta(1-\delta)}$ . Simplifying these two conditions together, we get  $c_2 \leq c$ . Also,  $p_r < \delta p_{n2}$ ,  $c+s < p_{n2}$  and  $q_r(p_{n2}, p_r) < \hat{q}(p_{n2}, c+s)$  are given by  $-(1-\delta)(1-p_{n1}) < 0$  (which is always true),  $\frac{\delta+c+s-1}{\delta} < p_{n1}$  and  $\frac{1-2\alpha+\alpha c+\alpha s+\alpha\delta}{1-\alpha+\alpha\delta} < p_{n1}$ .

Thus, there are 17 candidate solutions which can be summarized by three conditions, with mutually exclusive and collective exhaustive regions:

Condition 1 (Low  $c$ ) If  $c \leq c_1$ , Cases 3, 4, 11 and 12 hold.

Condition 2 (Medium  $c$ ) If  $c_1 < c < c_2$ , Cases 5a, 5b, 6a, 6b, 13a, 13b, 14a and 14b hold.

Condition 3 (High  $c$ ) If  $c_2 \leq c$ , Cases 7a, 7b, 8a, 8b, 15a, 15b, 16 hold. We can tabulate

the above cases as follows:

Condition 1: If  $c \leq c_1$ , the optimal cases can be summarized as  $p_{n1} < c + s$  &  $c < c_0$ ,  $p_{n1} < c + s$  &  $c_0 \leq c$  and  $c + s \leq p_{n1} < \bar{p}_a$  and  $\bar{p}_a \leq p_{n1}$ .

Condition 2: If  $c_1 < c < c_2$ , the optimal cases can be summarized as  $p_{n1} < \min(c + s, \bar{p}_i)$  &  $c < c_g$ ,  $p_{n1} < \min(c + s, \bar{p}_i)$  &  $c_g \leq c$ ,  $\bar{p}_i \leq p_{n1} < \min(c + s, \bar{p}_j)$ ,  $\bar{p}_j \leq p_{n1} < c + s$ ,  $c + s \leq p_{n1} < \min(\bar{p}_b, \bar{p}_c)$ ,  $\bar{p}_b \leq c < \bar{p}_c$ , and  $\bar{p}_c \leq c$ .

Condition 3: If  $c_2 \leq c$ , the optimal cases can be summarized as  $p_{n1} < \min(c + s, \bar{p}_k)$  &  $c < c_h$ ,  $p_{n1} < \min(c + s, \bar{p}_k)$  &  $c_h \leq c$ ,  $\bar{p}_k \leq p_{n1} < c + s$ ,  $c + s \leq p_{n1} < \min(\bar{p}_d, \bar{p}_e)$ ,  $\bar{p}_d \leq p_{n1} < \bar{p}_e$ , and  $\bar{p}_e \leq p_{n1}$ ,

$$\begin{aligned} \text{where } c_0 &\doteq 1 - 2s, \quad c_1 \doteq \frac{c_r - s}{\delta}, \quad c_2 \doteq \frac{c_r(2-\alpha) + 2(1-s)(1+\alpha\delta) + 3\alpha s - 2\alpha - 2\delta}{2-2\alpha+\alpha\delta}, \\ c_g &\doteq \frac{c_r(2-\alpha)(1-\alpha) + 2\alpha\delta(1-\delta)(1-2s(1-\alpha)) - s(1-\alpha)(2-\alpha\delta)}{\delta(2-\alpha+\alpha^2-2\alpha\delta)}, \quad \bar{p}_a \doteq \frac{(1-\alpha s) + c(1-\alpha)}{2-\alpha} \\ c_h &\doteq \frac{(c-r-s)^2(1-\alpha)^2 - \delta(1-\alpha)(1-3\alpha-\alpha c_r + 4\alpha s) - \alpha\delta^2 + 2\alpha^2\delta^2(1-s)}{\alpha\delta(2(1-\alpha) + \alpha\delta)}, \quad \bar{p}_b \doteq \frac{(c_r-s)(2-\alpha) + 2\delta(1-\alpha s) - \alpha\delta c}{2\delta(2-\alpha)}, \\ \bar{p}_c &\doteq \frac{(c_r+s)(1-\alpha)(2-\alpha) - 2\delta(1-\alpha s)(2-3\alpha+\alpha\delta) - \delta c(1-\alpha)(2-5\alpha+2\alpha\delta)}{2\alpha\delta(2-\alpha)(1-\delta)}, \quad \bar{p}_d \doteq \frac{(1-\alpha)(c_r-s+\delta) + \alpha\delta(\delta-s)}{\delta(2-2\alpha+\alpha\delta)}, \\ \bar{p}_e &\doteq \frac{(c_r-s)(1-\alpha)^2 + \alpha^2\delta^2(1-s) - \delta(1-\alpha)(1-\alpha c_r) + \alpha\delta(1-\alpha)(3-2s-\delta)}{\alpha\delta(2-2\alpha+\alpha\delta)}, \quad \bar{p}_i \doteq \frac{(c_r-s)(2-\alpha) + 2\delta(1-\alpha s) - \alpha\delta c}{2\delta(2-\alpha)}, \\ \bar{p}_j &\doteq \frac{-(c_r-s)(1-\alpha)(1-2\alpha+\alpha\delta) + (1-\alpha)(1+c)(1-\delta) - \alpha(1-\delta)(1-\alpha s)(1-\delta-s) + \alpha c(1-\delta)(1-\alpha\delta)}{(1-\alpha)(1-\delta)(2-\alpha+2\alpha\delta)} \quad \text{and} \\ \bar{p}_k &\doteq \frac{(1-\alpha)(c_r-s+\delta) + \alpha\delta(\delta-s)}{\delta(2(1-\alpha) + \alpha\delta)}. \end{aligned}$$

*First Period Analysis:* After characterizing the OEM's optimal second-period list price, we now solve for the optimal first-period list price decision. We maximize the total two-period profit  $\Pi^{MR}(p_{n1}) = (1 - p_{n1})(p_{n1} - c) + \Pi_2^{MR}(p_{n1})$  to determine  $p_{n1}$  and  $\Pi^{MR*} \doteq \Pi^{MR}(p_{n1})$ . First, we need to check whether the optimum lies in  $p_{n1} < c + s$  or  $c + s \leq p_{n1}$ . Cases 11, 12, 13a, 13b, 14a, 14b, 15a, 15b and 16 lie under the condition  $p_{n1} < c + s$  and Cases 3, 4, 5a, 5b, 6a, 6b, 7a, 7b, 8a and 8b lie under the condition  $c + s \leq p_{n1}$ . As discussed earlier, the optimal solutions are summarized by the following three conditions on  $c$ :

*Condition 1 (Low  $c$ )*  $c \leq c_1$ : First, we need to check whether the optimum lies in Case 3 ( $c + s \leq p_{n1}$ ) or Case 12 ( $p_{n1} < c + s$ ). The derivative of the two-period profit under Case 3, evaluated at  $c + s$  is given by  $1 - c - 2s$ . If this is positive [ $c < c_0 \doteq 1 - 2s$  or  $c < 1/3$ ], the optimum is reached at  $c + s \leq p_{n1}^*$  and cases from Scenario II are ruled out; if it is negative [ $c_0 \leq c$  or  $1/3 \leq c$ ], it is reached at  $p_{n1}^* \leq c + s$  and cases from Scenario I are ruled out. For cases under Scenario I, we first check whether the optimal  $p_{n1}^*$  lies under  $p_{n1}^* < \bar{p}_a$ , i.e. Case

3 or Case 4 which is defined by  $\bar{p}_a \leq p_{n1}^*$ . The derivative of the two-period profit under Case 3 evaluated at  $\bar{p}_a$  is given by  $-1 + c + 2s$ . If this is negative [ $c < c_0$  or  $c < 1/3$ ], then the optimum lies in Case 3 and is given by  $\frac{1+\alpha s+c(1+\alpha)}{2+\alpha}$ ; if it is positive, [ $c_0 \leq c$  or  $1/3 \leq c$ ], the optimum lies under Case 4 and is given by  $\frac{1+c}{2}$ . However,  $c < c_0$  defines the cases in this scenario and hence the optimum always lies under Case 3 and Case 4 is ruled out. For cases under Scenario II, Case 11 requires  $c < c_0$  which contradicts the condition [ $c_0 \leq c$ ] required for the optimum to lie under  $p_{n1} < c + s$  and is ruled out. Thus, if  $c_0 \leq c$ , only Case 12 holds and the optimum is given by  $p_{n1}^* = \frac{1+c}{2}$ .

*Condition 2 (Medium c)*  $c_1 < c < c_2$ : First, we need to check whether the optimum lies in Case 5a ( $c + s \leq p_{n1}$ ) or Case 14b ( $p_{n1} < c + s$ ). The derivative of the two-period profit under Case 5a, evaluated at  $c + s$  is given by  $1 - c - 2s$ . If this is positive [ $c < c_0 \div 1 - 2s$  or  $c < 1/3$ ], the optimum is reached at  $c + s \leq p_{n1}^*$  and cases from Scenario II are ruled out; if it is negative [ $c_0 \leq c$  or  $1/3 \leq c$ ], it is reached at  $p_{n1}^* \leq c + s$  and cases from Scenario I are ruled out. For cases under Scenario I, we now check whether the optimal  $p_{n1}^*$  lies under  $p_{n1}^* < \bar{p}_b$ , i.e. Case 5a or Case 6a which is defined by  $\bar{p}_b \leq p_{n1}^*$ . The derivative of the two-period profit under Case 5a evaluated at  $\bar{p}_b$  is given by  $2\delta(1-\alpha)c - (c_r - s)(2-\alpha) - \alpha\delta(1+2s) + 4\delta$ . If this is negative [ $c < \frac{(c_r-s)(2-\alpha)+\alpha\delta(1+2s)-4\delta}{2\delta(1-\alpha)} \doteq c_a$ ], then the optimum lies in Case 5a and is given by  $\frac{1+c}{2} \frac{1+\alpha s+c(1+\alpha)}{2+\alpha}$ ; if it is positive, [ $c_a \leq c$ ], the optimum lies under Case 6a and is given by  $\frac{c(2+\alpha-\alpha^2-2\alpha\delta)+c_r(2-\alpha)(1-\alpha)+(2-\alpha)+2\alpha s(1-\alpha)-2s(1+\alpha\delta)-\alpha\delta(3-\alpha s)+3\alpha s+2\delta}{4-\alpha^2+4\delta-8\alpha\delta+\alpha^2\delta}$ . Now we check whether the optimal decisions are constrained by the supply of recovered products, i.e. whether the optimum lies in Case 5b. The derivative of the two-period profit under Case 5b (which is defined by  $\bar{p}_c \leq p_{n1}$ ) evaluated at  $\bar{p}_c$  is given by  $\delta(4 - 8\alpha + 5\alpha^2 + 3\alpha^3 - 4\alpha^2\delta)c - (c_r + s)(4 - \alpha^2)(1 - \alpha) + 8\delta + 4\alpha^2\delta^2(1 - 2s) - 4\alpha\delta(1 + 2s + 2\alpha - 3\alpha s - \alpha^2 s)$ . If this is positive [ $\frac{(c_r+s)(4-\alpha^2)(1-\alpha)-8\delta-4\alpha^2\delta^2(1-2s)+4\alpha\delta(1+2s+2\alpha-3\alpha s-\alpha^2 s)}{\delta(4-8\alpha+5\alpha^2+3\alpha^3-4\alpha^2\delta)} \doteq c_b \leq c$ ], the optimum lies under Case 5b and is given by  $p_{n1}^2$  which is provided at the end of the appendix; if this is negative then the optimum lies under Case 5a or 6a (based on  $c_a$ ).

For cases under Scenario II, which require  $p_{n1} < \bar{p}_i$ , if  $c < c_g$ , then the optimum lies under Case 13a and is given by  $\frac{1+c}{2}$  and if  $c_g \leq c$ , then the optimum lies under Case 13b and is given by

$p_1^5 \doteq \frac{(1-\delta)((2-\alpha)(1+\alpha s) + \delta(1-2\alpha-\alpha s)) + c(2-3\delta + \alpha(1-\alpha-\delta+2\delta^2))}{4-\alpha^2-2\alpha\delta(1-2\delta)-\delta(4+\delta)}$ . Now we check whether the optimal  $p_{n1}^*$  lies under  $p_{n1}^* < \bar{p}_i$  (Case 13a & 13b) or  $\bar{p}_i \leq p_{n1}^*$  (Case 14a & 14b). The derivative of the total profit under Case 13a evaluated at  $\bar{p}_i$  is given by  $-(c_r - s)(2 - \alpha) + \alpha\delta(1 - 2s) + 2\delta c$ . If this is negative [ $c < c_k \doteq \frac{(c_r - s)(2 - \alpha) - \alpha\delta(1 - 2s)}{2\delta}$ ], the optimum lies under Case 13a or Case 13b (depending on value of  $c_g$ ); if it is positive [ $c_k \leq c$ ], then the optimum lies under Case 14a or Case 14b. Note that Case 14a is defined by  $p_{n1}^* < \bar{p}_j$  and Case 14b is defined by  $\bar{p}_j \leq p_{n1}^*$ . The derivative of the total profit under Case 14a evaluated at  $\bar{p}_j$  is given by  $c_r(1 - \alpha) + s(1 + \alpha) - (1 + \delta) + 2\delta s + 2\alpha\delta - 4\alpha\delta s + c(1 - \alpha\delta)$ . If this is negative [ $c < c_l \doteq \frac{1+\delta-(2\delta s+c_r)(1-\alpha)-2\alpha\delta(1-s)-s(1+\alpha)}{1-\alpha\delta}$ ], the optimum lies in Case 14a and is given by  $p_1^7 \doteq \frac{(2-\alpha)(1+c) + (2-\alpha)(1-\alpha)(c_r-s) - \alpha\delta c(2-\alpha) - 2\alpha\delta s(1-\alpha) + \delta(2-3\alpha)}{4(1+\delta) - 2\alpha(1+4\delta - \alpha\delta)}$ ; if it is positive [ $c_l \leq c$ ], it lies in Case 14b and is given by

$$p_1^6 \doteq \frac{2+\alpha^2(3-\delta)(2-\delta)+3\alpha\delta+s(1-\alpha)(1-\delta)(2-\alpha+2\alpha\delta)-\alpha c_r(1-\alpha)(1-2\alpha+\alpha\delta)-7\alpha+c(2-6\alpha+6\alpha^2-\alpha^3+2\alpha\delta-4\alpha^2\delta+\alpha^3\delta^2)}{4-12\alpha(1-\alpha)-\alpha-2\alpha^2\delta-\alpha^3+4\alpha\delta(1-\alpha)-2\alpha^3\delta(1-\delta)}.$$

*Condition 3 (High c)*  $c_2 \leq c$ : First, we need to check whether the optimum lies in Case 7a ( $c + s \leq p_{n1}$ ) or Case 16 ( $p_{n1} < c + s$ ). The derivative of the two-period profit under Case 7a, evaluated at  $c + s$  is given by  $1 - c - 2s$ . If this is positive [ $c < c_0 \doteq 1 - 2s$  or  $c < 1/3$ ], the optimum is reached at  $c + s \leq p_{n1}^*$  and cases from Scenario II are ruled out; if it is negative [ $c_0 \leq c$  or  $1/3 \leq c$ ], it is reached at  $p_{n1}^* \leq c + s$  and cases from Scenario I are ruled out.

For cases under Scenario I, we first check whether the optimal  $p_{n1}^*$  lies under  $p_{n1}^* < \bar{p}_d$ , i.e. Case 7a or Case 8a which is defined by  $\bar{p}_d \leq p_{n1}^*$ . The derivative of the two-period profit under Case 7a evaluated at  $\bar{p}_d$  is given by  $c\delta(2 - 2\alpha^2 + \alpha\delta + \alpha\delta^2) - (c_r - s)(2 - \alpha - \alpha^2) + \alpha^2\delta(1 - \delta)(1 - s) - \alpha\delta(1 - 4s - \delta)$ . If this is negative [ $c < \frac{(c_r - s)(2 - \alpha - \alpha^2) - \alpha^2\delta(1 - \delta)(1 - s) + \alpha\delta(1 - 4s - \delta)}{\delta(2 - 2\alpha^2 + \alpha\delta + \alpha\delta^2)} \doteq c_c$ ], then the optimum lies in Case 7a and is given by  $\frac{1+\alpha s+c(1+\alpha)}{2+\alpha}$ ; if it is positive, [ $c_c \leq c$ ], the optimum lies under Case 8a and is given by  $\frac{(c_r - s)(1 - \alpha) + \alpha s(1 - \delta) + c(1 + \alpha) + \delta(1 - \alpha) + (1 + \alpha\delta^2)}{\alpha(1 - \delta)^2 + 2(1 + \delta)}$ . Now we check whether the optimal decisions are constrained by the supply of recovered products, i.e. whether the optimum lies in Case 7b. The derivative of the two-period profit under Case 7b (which is defined by  $\bar{p}_e \leq p_{n1}$ ) evaluated at  $\bar{p}_e$  is given by  $c\alpha\delta(1 + \alpha)(2 - 2\alpha + \alpha\delta) - (1 + \alpha + \alpha\delta)(c_r(2 - \alpha)(1 - \alpha) - 2\delta) - \alpha\delta(1 - \alpha^2)(3 - 4s) - 2\alpha^2\delta^2(1 + \alpha)(1 - s) + s(1 - \alpha^2)(2 + \alpha)$ . If this is positive [ $\frac{(1 - \alpha + \alpha\delta)(c_r(2 - \alpha)(1 - \alpha) - 2\delta) + \alpha\delta(1 - \alpha^2)(3 - 4s) + 2\alpha^2\delta^2(1 + \alpha)(1 - s) - s(1 - \alpha^2)(2 + \alpha)}{\alpha\delta(1 + \alpha)(2 - 2\alpha + \alpha\delta)} \doteq c_d \leq c$ ], the optimum lies under 7b & is given by  $\frac{(1 - \alpha)^2(1 + \alpha c_r) + c(1 + \alpha)(1 - \alpha + \alpha\delta)^2 + \alpha\delta(1 - \alpha)(1 + 3\alpha + \alpha c_r) + 2\alpha^3\delta^2}{2 - 3\alpha + \alpha^3 + 4\alpha\delta(1 - \alpha^2) + 2\alpha^2\delta^2(1 + \alpha)}$ ;

if this is negative then the optimum lies under Case 7a or 8a (based on  $c_c$ ).

For cases under Scenario II, which require  $p_{n1} < \bar{p}_k$ , if  $c < c_h$ , then the optimum lies under Case 15a and is given by  $\frac{1+c}{2}$  and if  $c_h \leq c$ , then the optimum lies under Case 15b and is given by  $\frac{1+c}{2}$ . Now we check whether the optimal  $p_{n1}^*$  lies under  $p_{n1} < \bar{p}_k$  (Case 15a & Case 15b) or  $\bar{p}_k \leq p_{n1}$  (Case 16). The derivative of the total profit under Case 15a evaluated at  $\bar{p}_k$  is given by  $c\alpha\delta(2-2\alpha+\alpha\delta)-(c_r-s)(1-\alpha)^2+\delta(1-\alpha)(1-3\alpha-\alpha c_r+4\alpha s)+\alpha\delta^2-2\alpha^2\delta^2(1-s)$ . If this is negative [ $c < c_m \doteq \frac{(c_r-s)(1-\alpha)^2-\delta(1-\alpha)(1-3\alpha-\alpha c_r+4\alpha s)-\alpha\delta^2+2\alpha^2\delta^2(1-s)}{\alpha\delta(2-2\alpha+\alpha\delta)}$ ], the optimum lies under Case 15a and 15b (based on the value of  $c_h$ ); if it is positive [ $c_m \leq c$ ], the optimum lies under Case 16 and is given by  $\frac{1+(c_r-s+\delta)(1-\alpha)-\alpha\delta(s-\delta)+c}{2+2\delta(1-\alpha)+\alpha\delta^2}$ .

The two-period optimal decisions under  $c < c_0$  or  $c < 1/3$  are summarized in Proposition 2 and those under  $c_0 \leq c$  or  $1/3 \leq c$  are summarized below:

If the monopolist markets a trade-in rebate program for new products along with a remanufactured version of the product, then the monopolist's optimal strategy is dependent on its per-unit production cost  $c$  relative to other parameters as follows:

Condition 1 : If  $c \leq c_1$ , then the optimal prices are given by  $p_1^{MR*} = \frac{1+c}{2}$ ,  $p_{n2}^{MR*} = c + s$  and  $p_r^{MR*} = \delta(c + s)$ . In this case, the monopolist does not market remanufactured products ( $q_r^{MR*} = 0$ ), and consumers in both segments buy the new product ( $q_{n2,1-\alpha}^{MR*} > 0$ ,  $q_{n2,\alpha}^{MR*} > 0$ ).

Condition 2 If  $c_1 < c < c_2$ , then the optimal prices are given in the table below. In this case, the monopolist sells remanufactured products ( $q_r^{MR*} > 0$ ), and consumers in both segments buy new products ( $q_{n2,1-\alpha}^{MR*} > 0$  and  $q_{n2,\alpha}^{MR*} > 0$ ).

Condition 3 : (High  $c$ ) If  $c_2 \leq c$ , then the optimal prices are given in the table below. In this case, the monopolist sells remanufactured products ( $q_r^{MR*} > 0$ ), and the new product is only chosen by consumers in the  $\alpha$  segment ( $q_{n2,1-\alpha}^{MR*} = 0$ ,  $q_{n2,\alpha}^{MR*} > 0$ ).

**Proof of Proposition 3.** We can write the third-party remanufacturer's second-period problem is given by

$$\max_{p_r} \Pi_R^{DR} = (1-\alpha) \frac{(\delta p_{n2} - p_r)}{\delta(1-\delta)} (p_r - c_r)$$

$$s.t. \quad \delta p_{n1} \leq p_r \tag{42}$$

$$p_{n1} \leq \delta p_{n2} \tag{43}$$

Since  $\frac{\partial^2 \Pi_R^{DR}}{\partial p_r^2} = -\frac{2(1-\alpha)}{\delta(1-\delta)} < 0$ , the third-party remanufacturer's profit function is concave in  $p_r$  and the OEM's second-period problem is given by

$$\max_{p_{n2}} \Pi^{DR} = \alpha \left[ (1 - p_{n2})(p_{n2} - c) + \int_k^{p_{n2}} (\phi - c - s) d\phi \right] + (1 - \alpha) \left[ \left( 1 - \frac{p_{n2} - p_r}{1 - \delta} \right) (p_{n2} - c) \right]$$

$$s.t. \quad k \doteq \max(p_{n1}, c + s) \leq p_{n2} \quad (44)$$

$$p_{n2} \leq 1 - \delta + p_r \quad (45)$$

Since  $\frac{\partial^2 \Pi^{DR}}{\partial p_{n2}^2} = -\alpha - \frac{2(1-\alpha)}{1-\delta} < 0$  the OEM's profit function is concave in  $p_{n2}$ . If  $\lambda_i \geq 0 \forall i \in \{1, 2, 3, 4\}$ , the Lagrangian function for the third-party and OEM are given by

$$\mathbb{L}_R(p_{n2}, p_r, \lambda_1, \lambda_2) = (1 - \alpha) \frac{(\delta p_{n2} - p_r)}{\delta(1 - \delta)} (p_r - c_r) - \lambda_1 (\delta p_{n1} - p_r) - \lambda_2 (p_{n1} - \delta p_{n2})$$

$$\begin{aligned} \mathbb{L}(p_{n2}, p_r, \lambda_3, \lambda_4) = & \alpha \left[ (1 - p_{n2})(p_{n2} - c) + \int_k^{p_{n2}} (\phi - c - s) d\phi \right] \\ & + (1 - \alpha) \left[ \left( 1 - \frac{p_{n2} - p_r}{1 - \delta} \right) (p_{n2} - c) \right] - \lambda_3 (k - p_{n2}) - \lambda_4 (p_{n2} - 1 + \delta - p_r) \end{aligned} \quad (46)$$

The KKT conditions which are necessary and sufficient for optimality are given by  $\frac{\partial \mathbb{L}_R}{\partial p_r} = 0$ ,  $\frac{\partial \mathbb{L}}{\partial p_{n2}} = 0$ ,  $\lambda_1 (\delta p_{n1} - p_r) = 0$ ,  $\lambda_2 (p_{n1} - \delta p_{n2}) = 0$ ,  $\lambda_3 (k - p_{n2}) = 0$ ,  $\lambda_4 (p_{n2} - 1 + \delta - p_r) = 0$  and  $\lambda_i \geq 0 \forall i \in \{1, 2, 3, 4\}$ .

Solving  $\frac{\partial \mathbb{L}_R}{\partial p_r} = 0$  and  $\frac{\partial \mathbb{L}}{\partial p_{n2}} = 0$  together we get,

$$p_{n2}(\lambda_1, \lambda_2, \lambda_3, \lambda_4) = \frac{(1 - \alpha)(2c + c_r) + (1 - \delta)(2(1 - \alpha s) + 2(\lambda_3 - \lambda_4) + \delta(\lambda_1 - \lambda_2))}{4 - \delta - 2\alpha - \alpha\delta}$$

$$p_r(\lambda_1, \lambda_2, \lambda_3, \lambda_4) = ((2 - \alpha - \alpha\delta)(c_r(1 - \alpha) + \delta(1 - \delta)$$

$$(\lambda_1 - \lambda_2)) + \delta c(1 - \alpha)^2 + \delta(1 - \delta)(1 - \alpha)(1 - \alpha s + \lambda_3 - \lambda_4)) / ((1 - \alpha)(4 - \delta - 2\alpha - \alpha\delta))$$

There are two main scenarios to be analyzed based on whether  $\max(p_{n1}, c + s) = p_{n1}$  (*Scenario I*) or  $\max(p_{n1}, c + s) = c + s$  (*Scenario II*).

*Scenario I.* If  $c + s \leq p_{n1}$ , then we have  $k = p_{n1}$  and there are four main groups of cases to be analyzed based on whether the constraints  $p_r \leq \delta p_{n2}$  and  $p_{n2} \leq 1 - \delta + p_r$  are binding or slack.



*Group A:*  $p_r = \delta p_{n2}$  and  $p_{n2} = 1 - \delta + p_r$ , i.e.  $q_{n2,1-\alpha} = 0$  and  $q_r = 0$ .

In this group we have  $q_r = 0$  and we have two candidate cases; if  $\delta p_{n1} < p_r = \delta p_{n2}$ , then  $p_{n1} < p_{n2}$  has to hold true and if  $\delta p_{n1} = p_r = \delta p_{n2}$ , then only  $p_{n1} = p_{n2}$  is feasible.

*Case 1*  $\delta p_{n1} < p_r = \delta p_{n2}$  and  $p_{n1} < p_{n2} = 1 - \delta + p_r$ : In this case, (43) & (45) are binding and (42) & (44) are not binding, so we have  $\lambda_1 = \lambda_3 = 0$  and  $\lambda_2, \lambda_4 \geq 0$ . Solving  $p_r = \delta p_{n2}$  and  $p_{n2} = 1 - \delta + p_r$ , we get  $p_{n2} = 1$  and  $p_r = \delta$ . We can now solve  $p_{n2}(0, 0, 0, \lambda_4) = 1$  and  $p_r(0, \lambda_2, 0, \lambda_4) = \delta$  and we have  $\lambda_2 = -\frac{(1-c)(1-\alpha)+\alpha s(1-\delta)}{1-\delta} < 0$ . However, this contradicts  $\lambda_2 \geq 0$  and this case is ruled out.

*Case 2*  $\delta p_{n1} = p_r = \delta p_{n2}$  and  $p_{n1} = p_{n2} = 1 - \delta + p_r$ : In this case, (42), (43), (44) & (45) are binding. Solving  $p_{n1} = p_r = \delta p_{n2}$  and  $p_{n1} = p_{n2} = 1 - \delta + p_r$ , we get  $p_{n2} = 1$ ,  $p_r = \delta$  and  $p_{n1} = 1$ . However, this contradicts  $p_{n1} < 1$  and this case is ruled out.

*Group B:*  $p_r = \delta p_{n2}$  and  $p_{n2} < 1 - \delta + p_r$ , i.e.  $q_{n2,1-\alpha} > 0$  and  $q_r = 0$ .

In this group we have  $q_r = 0$  and we have two candidate solutions; if  $\delta p_{n1} < p_r = \delta p_{n2}$ , then  $p_{n1} < p_{n2}$  has to hold true and if  $\delta p_{n1} = p_r = \delta p_{n2}$ , then  $p_{n1} = p_{n2}$ .

*Case 3*  $\delta p_{n1} < p_r = \delta p_{n2}$  and  $p_{n1} < p_{n2} < 1 - \delta + p_r$ : In this case, (42), (44) & (45) are not binding and (43) is binding, so we have  $\lambda_1 = \lambda_3 = \lambda_4 = 0$  and  $\lambda_2 \geq 0$ . The optimal value of list price is given by  $p_{n2} = \frac{(1-\alpha s)(1-\delta)+c(1-\alpha)}{2-\alpha-\delta}$  and by solving  $p_r(0, \lambda_2, 0, 0, 0) = \delta p_{n2}(0, 0, 0, 0)$  we get  $\lambda_2 = c_r(2 - \alpha - \delta) - \delta(1 - \alpha s)(1 - \delta) - c\delta(1 - \alpha)$ . The conditions  $p_{n1} < p_{n2}$  and  $\lambda_2 \geq 0$  can be simplified to  $p_{n1} < \frac{(1-\alpha s)(1-\delta)+c(1-\alpha)}{2-\alpha-\delta}$  and  $c \leq c_3$  respectively, where  $c_3 \doteq \frac{c_r(2-\alpha-\delta)-\delta(1-\alpha s)(1-\delta)}{\delta(1-\alpha)}$ . Also, the conditions  $p_{n2} < 1 - \delta + p_r$  gives us  $p_{n2} < 1$  (which is always true).

*Case 4*  $\delta p_{n1} = p_r = \delta p_{n2}$  and  $p_{n1} = p_{n2} < 1 - \delta + p_r$ : In this case, (45) is not binding and (42), (43) & (44) are binding. Thus, we have  $p_r = \delta p_{n1}$ ,  $p_{n1} = p_{n2}$  and solving  $p_{n2}(0, 0, \lambda_3, 0) = p_{n1}$  and  $p_r(0, \lambda_2, \lambda_3, 0) = \delta p_{n1}$ , we get  $\lambda_2 = c_r - \delta p_{n1}$  and  $\lambda_3 = p_{n1}(2 - \alpha - \delta) - (1 - \delta)(1 - \alpha s) + c(1 - \alpha)$ . The conditions  $\lambda_2, \lambda_3 \geq 0$  give us  $p_{n1} \leq \frac{c_r}{\delta}$  and  $\frac{(1-\delta)(1-\alpha s)+c(1-\alpha)}{2-\alpha-\delta} \leq p_{n1}$  respectively. Both of these conditions can be simplified together to  $c \leq c_3$ .

*Group C:*  $p_r < \delta p_{n2}$  and  $p_{n2} < 1 - \delta + p_r$ , i.e.  $q_{n2,1-\alpha} > 0$  and  $q_r > 0$ . In this group, since  $\delta p_{n1} \leq p_r$  we always have  $p_{n1} < p_{n2}$ . We have two candidate solutions;  $\delta p_{n1} < p_r < \delta p_{n2}$

and  $\delta p_{n1} = p_r < \delta p_{n2}$ .

*Case 5*  $\delta p_{n1} < p_r < \delta p_{n2}$  and  $p_{n1} < p_{n2} < 1 - \delta + p_r$ : In this case, (42), (43), (44) & (45) are not binding, so we have  $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = 0$ . The optimal prices are given by  $p_{n2} = p_{n2}(0, 0, 0, 0) = \frac{(1-\alpha)(2c+c_r)+2(1-\alpha s)(1-\delta)}{4-\delta-2\alpha-\alpha\delta}$  and  $p_r = p_r(0, 0, 0, 0) = \frac{c_r(2-\alpha-\alpha\delta)+\delta(1-\delta)(1-\alpha s)+\delta c(1-\alpha)}{4-\delta-2\alpha-\alpha\delta}$ . The conditions  $\delta p_{n1} < p_r$ ,  $p_{n1} < p_{n2}$ ,  $p_r < \delta p_{n2}$  and  $p_{n2} < 1 - \delta + p_r$  are given by  $p_{n1} \leq \frac{c_r(2-\alpha-\alpha\delta)+\delta(1-\delta)(1-\alpha s)+\delta c(1-\alpha)}{\delta(4-\delta-2\alpha-\alpha\delta)}$ ,  $p_{n1} < \frac{(1-\alpha)(2c+c_r)+2(1-\alpha s)(1-\delta)}{4-\delta-2\alpha-\alpha\delta}$ ,  $c_3 < c$ , and  $c < c_4 \doteq \frac{c_r(1-\alpha\delta)+\alpha s(1-\delta)^2+2(1-\alpha)(1-\delta)+\alpha(1-\delta)(s-\delta)}{(1-\alpha)(2-\delta)}$  respectively.

*Case 6*  $\delta p_{n1} = p_r < \delta p_{n2}$  and  $p_{n1} < p_{n2} < 1 - \delta + p_r$ : In this case, (42) is binding and (43), (44) & (45) are not binding, so we have  $\lambda_2 = \lambda_3 = \lambda_4 = 0$  and  $\lambda_1 \geq 0$ . Solving  $p_{n2}(\lambda_1, 0, 0, 0) = p_{n2}$  &  $p_r(\lambda_1, 0, 0, 0) = \delta p_{n1}$  we get,  $p_{n2} = \frac{(1-\alpha s)(1-\delta)+c(1-\alpha)+\delta p_{n1}(1-\alpha)}{2-\alpha-\alpha\delta}$  and  $\lambda_1 = \delta p_{n1}(4-\delta-2\alpha-\alpha\delta) - c_r(2-\alpha-\alpha\delta) - \delta(1-\delta)(1-\alpha s) - \delta c(1-\alpha)$ . The conditions  $p_{n1} < p_{n2}$  and  $p_r < \delta p_{n2}$  are both given by  $p_{n1} < \frac{c(1-\alpha)+(1-\delta)(1-\alpha s)}{2-\alpha-\delta}$ . However,  $p_{n2} < 1 - \delta + p_r$  and  $\lambda_1 \geq 0$  are given by  $\frac{\delta(1-\alpha\delta)+\alpha s(1-\delta)-(1-\alpha)(1-c)}{\delta(1-\alpha\delta)} < p_{n1}$  and  $\frac{c_r(2-\alpha-\alpha\delta)+\delta(1-\delta)(1-\alpha s)+\delta c(1-\alpha)}{\delta p_{n1}(4-\delta-2\alpha-\alpha\delta)} \leq p_{n1}$ . Simplifying the above conditions we get  $c < c_4$ .

*Group D:*  $p_r < \delta p_{n2}$  and  $p_{n2} = 1 - \delta + p_r$ , i.e.  $q_{n2,1-\alpha} = 0$  and  $q_r > 0$ . In this group, since  $\delta p_{n1} \leq p_r$  we always have  $p_{n1} < p_{n2}$ . We have two candidate solutions;  $\delta p_{n1} < p_r < \delta p_{n2}$  and  $\delta p_{n1} = p_r < \delta p_{n2}$ .

*Case 7*  $\delta p_{n1} < p_r < \delta p_{n2}$  and  $p_{n1} < p_{n2} = 1 - \delta + p_r$ : In this case, (45) is binding and (42), (43) & (44) are not binding, so we have  $\lambda_1 = \lambda_2 = \lambda_3 = 0$  and  $\lambda_4 \geq 0$ . Solving  $p_{n2}(0, 0, 0, \lambda_4) = 1 - \delta + p_r(0, 0, 0, \lambda_4)$  and  $p_r(0, 0, 0, \lambda_4) = p_r$  together, we get  $p_r = \frac{c_r+\delta(1-\delta)}{2-\delta}$  and  $\lambda_4 = c(1-\alpha)(2-\delta) - c_r(1-\alpha\delta) - \alpha s(1-\delta)^2 - 2(1-\alpha)(1-\delta) - \alpha(1-\delta)(s-\delta)$ . The conditions  $\delta p_{n1} < p_r$ ,  $p_{n1} < p_{n2}$  and  $\lambda_4 \geq 0$  are given by  $p_{n1} < \frac{c_r+\delta(1-\delta)}{\delta(2-\delta)}$ ,  $p_{n1} < \frac{c_r+2(1-\delta)}{2-\delta}$ , and  $c_4 \leq c$ .

*Case 8*  $\delta p_{n1} = p_r < \delta p_{n2}$  and  $p_{n1} < p_{n2} = 1 - \delta + p_r$ : In this case, (42) & (45) are binding and (43) & (44) are not binding, so we have  $\lambda_2 = \lambda_3 = 0$  and  $\lambda_1, \lambda_4 \geq 0$ . In this case, we have  $p_r = \delta p_{n1}$ ,  $p_{n2} = 1 - \delta + p_r = 1 - \delta + \delta p_{n1}$  and solving  $p_{n2}(\lambda_1, 0, 0, \lambda_4) = 1 - \delta + \delta p_{n1}$  and  $p_r(\lambda_1, 0, 0, \lambda_4) = \delta p_{n1}$ , we get  $\lambda_1 = p_{n1}\delta(2-\delta) - c_r - \delta(1-\delta)$  and  $\lambda_4 = \delta(1-\alpha\delta) - \alpha s(1-\delta) - (1-\alpha)(1-c) - \delta p_{n1}(1-\alpha\delta)$ . The conditions  $\lambda_1, \lambda_4 \geq 0$  give us  $\frac{c_r+\delta(1-\delta)}{\delta(2-\delta)} \leq p_{n1}$  and  $p_{n1} \leq \frac{\delta(1-\alpha\delta)-\alpha s(1-\delta)-(1-\alpha)(1-c)}{\delta(1-\alpha\delta)}$ . Simplifying these two conditions

together, we get  $c_4 \leq c$ .

*Scenario II.* If  $p_{n1} < c + s$ , then we have  $k = c + s$  and there are four main groups of cases to be analyzed, depending on whether the constraints  $p_r \leq \delta p_{n2}$  and  $p_{n2} \leq 1 - \delta + p_r$  are binding or slack.

*Group A:*  $p_r = \delta p_{n2}$  and  $p_{n2} = 1 - \delta + p_r$ , i.e.  $q_{n2,1-\alpha} = 0$  and  $q_r = 0$ .

In this group we have  $q_r = 0$  and since  $\delta p_{n1} = p_r$  leads to  $p_{n1} = p_{n2}$  which is infeasible under this scenario, we can only have  $\delta p_{n1} < p_r$ . Thus, we have two candidate solutions;  $c + s < p_{n2}$  and  $c + s = p_{n2}$ .

*Case 9*  $\delta p_{n1} < p_r = \delta p_{n2}$  and  $c + s < p_{n2} = 1 - \delta + p_r$ : In this case, (43) & (45) are binding and (42) & (44) are not binding, so we have  $\lambda_1 = \lambda_3 = 0$  and  $\lambda_2, \lambda_4 \geq 0$ . Solving  $p_r = \delta p_{n2}$  and  $p_{n2} = 1 - \delta + p_r$ , we get  $p_{n2} = 1$  and  $p_r = \delta$ . We can now solve  $p_{n2}(0, 0, 0, \lambda_4) = 1$  and  $p_r(0, \lambda_2, 0, \lambda_4) = \delta$  and we get  $\lambda_4 = -\frac{(1-c)(1-\alpha)+(1-\alpha s)(1-\delta)}{1-\delta} < 0$ . However, this contradicts  $\lambda_4 \geq 0$  and this case is ruled out.

*Case 10*  $\delta p_{n1} < p_r = \delta p_{n2}$  and  $c + s = p_{n2} = 1 - \delta + p_r$ : In this case, (43), (44) & (45) are binding and (42) is not binding. Solving  $p_{n1} < p_r = \delta p_{n2}$  and  $c + s = p_{n2} = 1 - \delta + p_r$ , we get  $p_{n2} = 1 = c + s$ . However, this contradicts  $c + s < 1$  and this case is ruled out.

*Group B:*  $p_r = \delta p_{n2}$  and  $p_{n2} < 1 - \delta + p_r$ , i.e.  $q_{n2,1-\alpha} > 0$  and  $q_r = 0$ .

In this group we have  $q_r = 0$  and since  $\delta p_{n1} = p_r$  leads to  $p_{n1} = p_{n2}$  which is infeasible under this scenario, we can only have  $\delta p_{n1} < p_r$ . Thus, we have two candidate solutions;  $c + s < p_{n2}$  and  $c + s = p_{n2}$ .

*Case 11*  $\delta p_{n1} < p_r = \delta p_{n2}$  and  $c + s < p_{n2} < 1 - \delta + p_r$ : In this case, (42), (44) & (45) are not binding and (43) is binding, so we have  $\lambda_1 = \lambda_3 = \lambda_4 = 0$  and  $\lambda_2 \geq 0$ . The optimal value of list price is given by  $p_{n2} = \frac{(1-\alpha s)(1-\delta)+c(1-\alpha)}{2-\alpha-\delta}$  and by solving  $p_r(0, \lambda_2, 0, 0, 0) = \delta p_{n2}(0, 0, 0, 0)$  we get  $\lambda_2 = c_r(2 - \alpha - \delta) - \delta(1 - \alpha s)(1 - \delta) - c\delta(1 - \alpha)$ . The conditions  $c + s < p_{n2}$  and  $\lambda_2 \geq 0$  can be simplified to  $c < \frac{(1-\delta)(1-s)-s(1-\alpha\delta)}{(1-\delta)}$  and  $c \leq c_3$  respectively.

*Case 12*  $\delta p_{n1} < p_r = \delta p_{n2}$  and  $c + s = p_{n2} < 1 - \delta + p_r$ : In this case, (45) & (42) are not binding and (43) & (44) are binding. Thus, we have  $p_r = \delta(c + s)$ ,  $p_{n2} = c + s$  and solving  $p_{n2}(0, 0, \lambda_3, 0) = c + s$  and  $p_r(0, \lambda_2, \lambda_3, 0) = \delta(c + s)$ , we get  $\lambda_2 = c_r - \delta(c + s)$  and  $\lambda_3 = c(1 - \delta) + s(1 - \alpha\delta) - (1 - \delta)(1 - s)$ . The conditions  $\lambda_2, \lambda_3 \geq 0$  give us  $\delta(c + s) \leq c_r$

and  $\frac{(1-\delta)(1-s)-s(1-\alpha\delta)}{(1-\delta)} \leq c$  respectively.

*Group C:*  $p_r < \delta p_{n2}$  and  $p_{n2} < 1 - \delta + p_r$ , i.e.  $q_{n2,1-\alpha} > 0$  and  $q_r > 0$ . In this group, we have four candidate solutions based on whether  $\delta p_{n1} < p_r$  or  $\delta p_{n1} = p_r$  and whether  $c + s < p_{n2}$  or  $c + s = p_{n2}$ .

*Case 13*  $\delta p_{n1} < p_r < \delta p_{n2}$  and  $c + s < p_{n2} < 1 - \delta + p_r$ : In this case, (42), (43), (44) & (45) are not binding, so we have  $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = 0$ . The optimal prices are given by  $p_{n2} = p_{n2}(0, 0, 0, 0) = \frac{(1-\alpha)(2c+c_r)+2(1-\alpha s)(1-\delta)}{4-\delta-2\alpha-\alpha\delta}$  and  $p_r = p_r(0, 0, 0, 0) = \frac{c_r(2-\alpha-\alpha\delta)+\delta(1-\delta)(1-\alpha s)+\delta c(1-\alpha)}{4-\delta-2\alpha-\alpha\delta}$ . The conditions  $\delta p_{n1} < p_r$ ,  $c + s < p_{n2}$ ,  $p_r < \delta p_{n2}$  and  $p_{n2} < 1 - \delta + p_r$  are given by  $p_{n1} \leq \frac{c_r(2-\alpha-\alpha\delta)+\delta(1-\delta)(1-\alpha s)+\delta c(1-\alpha)}{\delta(4-\delta-2\alpha-\alpha\delta)}$ ,  $c < \frac{c_r(1-\alpha)+2(1-s)-\delta(2-s)+3\alpha\delta s}{2-\delta-\alpha\delta}$ ,  $c_3 < c$ , and  $c < c_4 = \frac{c_r(1-\alpha\delta)+\alpha s(1-\delta)^2+2(1-\alpha)(1-\delta)+\alpha(1-\delta)(s-\delta)}{(1-\alpha)(2-\delta)}$  respectively.

*Case 14*  $\delta p_{n1} < p_r < \delta p_{n2}$  and  $c + s = p_{n2} < 1 - \delta + p_r$ : In this case, (42), (43) & (45) are not binding and (44) is binding so we have  $\lambda_1 = \lambda_2 = \lambda_4 = 0$ . We have  $p_{n2} = c + s$  and solving  $c + s = p_{n2}(0, 0, \lambda_3, 0)$  and  $p_r = p_r(0, 0, \lambda_3, 0)$  together we get  $p_r = \frac{c_r+\delta c+\delta s}{2}$  and  $\lambda_3 = c(2-\delta-\alpha\delta) - c_r(1-\alpha) - 2(1-s) + \delta(2-s) - 3\alpha\delta s$ . The conditions  $\lambda_3 \geq 0$ ,  $\delta p_{n1} < p_r$  and  $p_r < \delta p_{n2}$  are given by  $\frac{c_r(1-\alpha\delta)+\alpha s(1-\delta)^2+2(1-\alpha)(1-\delta)+\alpha(1-\delta)(s-\delta)}{(1-\alpha)(2-\delta)} \leq c$ ,  $p_{n1} < \frac{c_r+\delta c+\delta s}{2\delta}$  and  $c_r < \delta(c + s)$  respectively.

*Case 15*  $\delta p_{n1} = p_r < \delta p_{n2}$  and  $c + s < p_{n2} < 1 - \delta + p_r$ : In this case, (42) is binding and (43), (44) & (45) are not binding, so we have  $\lambda_2 = \lambda_3 = \lambda_4 = 0$  and  $\lambda_1 \geq 0$ . Solving  $p_{n2}(\lambda_1, 0, 0, 0) = p_{n2}$  and  $p_r(\lambda_1, 0, 0, 0) = \delta p_{n1}$  together we get,  $p_{n2} = \frac{(1-\alpha s)(1-\delta)+c(1-\alpha)+\delta p_{n1}(1-\alpha)}{2-\alpha-\alpha\delta}$  and  $\lambda_1 = \delta p_{n1}(4-\delta-2\alpha-\alpha\delta) - c_r(2-\alpha-\alpha\delta) - \delta(1-\delta)(1-\alpha s) - \delta c(1-\alpha)$ . The conditions  $c + s < p_{n2}$  and  $p_r < \delta p_{n2}$  are given by  $\frac{(1-\alpha\delta)(c+2s)+(1-\delta)}{\delta(1-\alpha)} < p_{n1}$  and  $p_{n1} < \frac{c(1-\alpha)+(1-\delta)(1-\alpha s)}{2-\alpha-\delta}$ . However,  $p_{n2} < 1 - \delta + p_r$  and  $\lambda_1 \geq 0$  are given by  $\frac{\delta(1-\alpha\delta)+\alpha s(1-\delta)-(1-\alpha)(1-c)}{\delta(1-\alpha\delta)} < p_{n1}$  and  $\frac{c_r(2-\alpha-\alpha\delta)+\delta(1-\delta)(1-\alpha s)+\delta c(1-\alpha)}{\delta p_{n1}(4-\delta-2\alpha-\alpha\delta)} \leq p_{n1}$ . Simplifying the above conditions we get  $c < c_4$ .

*Case 16*  $\delta p_{n1} = p_r < \delta p_{n2}$  and  $c + s = p_{n2} < 1 - \delta + p_r$ : In this case, (42) & (44) are binding and (43) & (45) are not binding, so we have  $\lambda_2 = \lambda_4 = 0$  and  $\lambda_1, \lambda_3 \geq 0$ . Solving  $p_{n2}(\lambda_1, 0, \lambda_3, 0) = c + s$  and  $p_r(\lambda_1, 0, \lambda_3, 0) = \delta p_{n1}$ , we get  $\lambda_1 = 2\delta p_{n1} - c_r - \delta c - \delta s$  and  $\lambda_3 = (1-\alpha\delta)(c+2s) + (1-\delta) - \delta(1-\alpha)p_{n1}$ . The conditions  $\lambda_1 \geq 0$  and  $\lambda_3 \geq 0$  give us  $\frac{c_r+\delta c+\delta s}{2\delta} \leq p_{n1}$  and  $p_{n1} \leq \frac{(1-\alpha\delta)(c+2s)+(1-\delta)}{\delta(1-\alpha)}$ . Also,  $p_{n1} < p_{n2}$  gives us  $1 - 2s + \frac{\delta s(1-\alpha)}{1-\delta} < c$ .

*Group D:*  $p_r < \delta p_{n2}$  and  $p_{n2} = 1 - \delta + p_r$ , i.e.  $q_{n2,1-\alpha} = 0$  and  $q_r > 0$ . In this group, we have four candidate solutions based on whether  $\delta p_{n1} < p_r$  or  $\delta p_{n1} = p_r$  and whether  $c + s < p_{n2}$  or  $c + s = p_{n2}$ .

*Case 17*  $\delta p_{n1} < p_r < \delta p_{n2}$  and  $c + s < p_{n2} = 1 - \delta + p_r$ : In this case, (45) is binding and (42), (43) & (44) are not binding, so we have  $\lambda_1 = \lambda_2 = \lambda_3 = 0$  and  $\lambda_4 \geq 0$ . Solving  $p_{n2}(0, 0, 0, \lambda_4) = 1 - \delta + p_r(0, 0, 0, \lambda_4)$  and  $p_r(0, 0, 0, \lambda_4) = p_r$  together, we get  $p_r = \frac{c_r + \delta(1-\delta)}{2-\delta}$  and  $\lambda_4 = c(1-\alpha)(2-\delta) - c_r(1-\alpha\delta) - \alpha s(1-\delta)^2 - 2(1-\alpha)(1-\delta) - \alpha(1-\delta)(s-\delta)$ . The conditions  $\delta p_{n1} < p_r$ ,  $c + s < p_{n2}$  and  $\lambda_4 \geq 0$  are given by  $p_{n1} < \frac{c_r + \delta(1-\delta)}{\delta(2-\delta)}$ ,  $c < \frac{2(1-\delta) + c_r - s(2-\delta)}{2-\delta}$ , and  $c_4 \leq c$ .

*Case 18*  $\delta p_{n1} < p_r < \delta p_{n2}$  and  $c + s = p_{n2} = 1 - \delta + p_r$ : In this case, (45) & (44) are binding and (42) & (43) are not binding, so we have  $\lambda_1 = \lambda_2 = 0$  and  $\lambda_3, \lambda_4 \geq 0$ . Thus, we have  $p_{n2} = c + s$  and  $p_r = c + s - 1 + \delta$  and  $\lambda_3 = c(2-\delta) - 2(1-\delta) - c - r + s(2-\delta)$ . Thus, the conditions  $\delta p_{n1} < p_r$  and  $\lambda_3 \geq 0$  are given by  $p_{n1} < \frac{c+s-1+\delta}{\delta}$  and  $\frac{2(1-\delta) + c_r - s(2-\delta)}{2-\delta} \leq c$ .

*Case 19*  $\delta p_{n1} = p_r < \delta p_{n2}$  and  $c + s < p_{n2} = 1 - \delta + p_r$ : In this case, (42) & (45) are binding and (43) & (44) are not binding, so we have  $\lambda_2 = \lambda_3 = 0$  and  $\lambda_1, \lambda_4 \geq 0$ . In this case, we have  $p_r = \delta p_{n1}$ ,  $p_{n2} = 1 - \delta + p_r = 1 - \delta + \delta p_{n1}$  and solving  $p_{n2}(\lambda_1, 0, 0, \lambda_4) = 1 - \delta + \delta p_{n1}$  and  $p_r(\lambda_1, 0, 0, \lambda_4) = \delta p_{n1}$ , we get  $\lambda_1 = p_{n1}\delta(2-\delta) - c_r - \delta(1-\delta)$  and  $\lambda_4 = \delta(1-\alpha\delta) - \alpha s(1-\delta) - (1-\alpha)(1-c) - \delta p_{n1}(1-\alpha\delta)$ . The conditions  $\lambda_1, \lambda_4 \geq 0$  give us  $\frac{c_r + \delta(1-\delta)}{\delta(2-\delta)} \leq p_{n1}$  and  $p_{n1} \leq \frac{\delta(1-\alpha\delta) - \alpha s(1-\delta) - (1-\alpha)(1-c)}{\delta(1-\alpha\delta)}$ . Simplifying these two conditions together, we get  $c_4 \leq c$ . Also,  $c + s < p_{n2}$  gives us  $\frac{c+s-1+\delta}{\delta} < p_{n1}$ .

*Case 20*  $\delta p_{n1} = p_r < \delta p_{n2}$  and  $c + s = p_{n2} = 1 - \delta + p_r$ : In this case, (42), (44) & (45) are binding and (43) is not binding, so we have  $\lambda_2 = 0$  and  $\lambda_1, \lambda_3, \lambda_4 \geq 0$ . In this case, we have  $p_{n2} = c + s$ ,  $p_r = c + s - 1 + \delta$  and the following two conditions are required  $p_{n1} \leq \frac{c+s-1+\delta}{\delta}$  and  $\frac{c+s-1+\delta}{\delta} p_{n1}$  which cannot hold together and this case is ruled out.

Thus, there are 20 candidate solutions which can be summarized by three conditions, with mutually exclusive and collective exhaustive regions:

Condition 1 (Low  $c$ ) If  $c \leq c_3$ , Cases 3, 4, 11 and 12 hold.

Condition 2 (Medium  $c$ ) If  $c_3 < c < c_4$ , Cases 5, 6, 13, 14, 15 and 16 hold.

Condition 3 (High  $c$ ) If  $c_4 \leq c$ , Cases 7, 8, 17, 18 and 19 hold.

*First Period Analysis:* After characterizing the OEM's and third-party's optimal second-period decisions, we now move to the first-period decisions. The OEM maximizes her total two-period profit  $\Pi^{DR}(p_{n1}) = (1 - p_{n1})(p_{n1} - c) + \Pi_2^{DR}(p_{n1})$  to determine  $p_{n1}^{DR*}$  and  $\Pi^{DR*} \doteq \Pi^{DR}(p_{n1}^{DR*})$ . First, we need to check whether the optimum lies in  $p_{n1} < c + s$  or  $c + s \leq p_{n1}$ . Cases 11, 12, 13, 14, 15, 16, 17, 18 and 19 have the condition  $p_{n1} < c + s$  and Cases 3, 4, 5, 6, 7 and 8 lie under the condition  $c + s \leq p_{n1}$ . The optimal solutions are summarized by the following three conditions on  $c$ :

*Condition 1 (Low  $c$ )*  $c \leq c_3$ : First, we need to check whether the optimum lies in Case 12 or Case 3. The derivative of the two-period profit under Case 3, evaluated at  $c + s$  is given by  $1 - c - 2s$ . If this is positive [ $c < c_0 \doteq 1 - 2s$  or  $c < 1/3$ ], the optimum is reached at  $c + s \leq p_{n1}^*$  and cases from Scenario II are ruled out; if it is negative [ $c_0 \leq c$  or  $1/3 \leq c$ ], it is reached at  $p_{n1}^* \leq c + s$  and cases from Scenario I are ruled out. For cases under Scenario I, we check whether the optimal  $p_{n1}^*$  lies under  $p_{n1}^* < \bar{p}_f$ , i.e. Case 3 or Case 4 which is defined by  $\bar{p}_f \leq p_{n1}^*$ . The derivative of the two-period profit under Case 3 evaluated at  $\bar{p}_a$  is given by  $2\alpha(1 - c - 2s) + \delta(1 + c)(1 + \alpha)$ , which is always positive. Thus, the optimum lies in Case 3 and is given by  $\frac{1+\alpha s+c(1+\alpha)}{2+\alpha}$ . We now focus on cases under Scenario II, if  $c < c_n$  then the optimum lies in Case 11 and is given by  $\frac{1+c}{2}$  and if  $c_n \leq c$ , then it lies in Case 12 and is given by  $\frac{1+c}{2}$ .

*Condition 2 (Medium  $c$ )*  $c_3 < c < c_4$ : First, we need to check whether the optimum lies in Case 16 or Case 5. The derivative of the two-period profit under Case 5, evaluated at  $c + s$  is given by  $1 - c - 2s$ . If this is positive [ $c < c_0 \doteq 1 - 2s$  or  $c < 1/3$ ], the optimum is reached at  $c + s \leq p_{n1}^*$  and cases from Scenario II are ruled out; if it is negative [ $c_0 \leq c$  or  $1/3 \leq c$ ], it is reached at  $p_{n1}^* \leq c + s$  and cases from Scenario I are ruled out. For cases under Scenario I, we check whether the optimal  $p_{n1}^*$  lies under  $p_{n1}^* < \bar{p}_g$ , i.e. Case 5 or Case 6 which is defined by  $\bar{p}_g \leq p_{n1}^*$ . The derivative of the two-period profit under Case 5 evaluated at  $\bar{p}_b$  is given by  $\delta c(2 - \delta + 3\alpha - \alpha^2 - 2\alpha\delta - \alpha^2\delta) - c_r(2 + \alpha)(2 - \alpha - \alpha\delta) + \delta(2 + \delta - \alpha(3 - s(6 - \alpha - 3\delta - 2\alpha\delta)))$ . If this is negative [ $c < \frac{c_r(2+\alpha)(2-\alpha-\alpha\delta)-\delta(2+\delta-\alpha(3-s(6-\alpha-3\delta-2\alpha\delta)))}{\delta(2-\delta+3\alpha-\alpha^2-2\alpha\delta-\alpha^2\delta)} \doteq c_e$ ], then the optimum lies in Case 5 and is given by  $\frac{1+c(1+\alpha)+\alpha s}{2+\alpha}$ ; if it is positive, [ $c_e \leq c$ ], the optimum lies under Case

6 and is given by  $\frac{(1-\delta)((2-\alpha)(1+\alpha s)+\delta(1-2\alpha-\alpha s))+c(2-3\delta+\alpha(1-\alpha-\delta+2\delta^2))}{4-\alpha^2-2\alpha\delta(1-2\delta)-\delta(4+\delta)}$ . However, under Case 6 for  $p_{n1} > 0$ , we need  $\Delta_a \doteq -(1-c)(\alpha-\delta)+2\alpha s(1-\delta) \leq 0$ . This implies that if  $\Delta_a > 0$ , then the optimum lies in Case 5. Thus, if  $c < c_e$  or  $c_e \leq c$  and  $\Delta_a > 0$ , then the optimum lies in Case 5 and if  $c_e \leq c$  and  $\Delta_a \leq 0$ , then the optimum lies in Case 6.

As discussed above cases under scenario II, Cases 13, 14, 15 and 16 require  $c_0 \leq c_q$  and Case 14 also requires  $c_0 + \frac{\delta s(1-\alpha)}{1-\delta} < c$ . If  $c_0 \leq c \leq c_0 + \frac{\delta s(1-\alpha)}{1-\delta}$ , only Cases 13, 15 and 16 hold. First, we check whether the optimal  $p_{n1}^*$  lies under  $p_{n1} < \bar{p}_g$ , i.e. Case 13 & 14 or  $\bar{p}_g \leq p_{n1}$ , i.e. Case 15 & 16. The derivative of the total profit under Case 15 evaluated at  $\bar{p}_g$  is given by  $-2c_r(2-\alpha-\alpha\delta)+\delta(1-\alpha)(2+\delta)+2\alpha\delta s(1-\delta)+c\delta(2-\delta-\alpha\delta)$ . If this is positive  $[\frac{2c_r(2-\alpha-\alpha\delta)-\delta(1-\alpha)(2+\delta)-2\alpha\delta s(1-\delta)}{\delta(2-\delta-\alpha\delta)} \doteq c_s \leq c]$ , the optimum lies under either Case 15 or Case 16 and if it is negative  $[c < c_s]$ , it lies under Case 14 or Case 13. If  $c < c_s$  and  $c < c_p$ , the optimum lies under 13 and is given by  $\frac{1+c}{2}$  and if  $c_p \leq c$  it lies under 14 and is given by  $\frac{1+c}{2}$ . If  $c_s \leq c$  holds and suppose that  $c \leq c_0 + \frac{\delta s(1-\alpha)}{1-\delta}$  holds, the optimum lies under Case 15 and is given by  $\frac{c(2-\alpha-\delta(3-\alpha))+\alpha\delta^2(2-\alpha)+(1-\delta)(2+\delta-\alpha(1+\delta(2+s(1-\alpha))))}{4-\delta(4+\delta)+\alpha(2-\delta^2(4-\alpha))}$ . However, if  $c_0 + \frac{\delta s(1-\alpha)}{1-\delta} < c$ , then we need to check whether the optimal  $p_{n1}^*$  lies under  $p_{n1}^* < \bar{p}_l$  (Case 15) or  $\bar{p}_l \leq p_{n1}^*$  (Case 16). The derivative of the total profit under Case 16 evaluated at  $\bar{p}_l$  is given by  $c((2-\delta-\alpha\delta)(1-\delta))-\delta^2 s(1-\alpha)^2+4s(1-\delta)(1-\alpha\delta)+(1-\delta)(2-3\delta+\alpha\delta)$ . If this is positive  $[\frac{\delta^2 s(1-\alpha)^2-4s(1-\delta)(1-\alpha\delta)-(1-\delta)(2-3\delta+\alpha\delta)}{(2-\delta-\alpha\delta)(1-\delta)} \doteq c_t \leq c]$ , the optimum lies under Case 16 and is given by  $\frac{(1-\delta)(1+c)+\delta s(1-\alpha)}{2(1-\delta)}$  and if this is negative  $[c < c_t]$ , the optimum lies under Case 15.

*Condition 3 (High c)*  $c_4 \leq c$ : First, we need to check whether the optimum lies in Case 19 or Case 7. The derivative of the two-period profit under Case 7, evaluated at  $c+s$  is given by  $1-c-2s$ . If this is positive  $[c < c_0 \doteq 1-2s \text{ or } c < 1/3]$ , the optimum is reached at  $c+s \leq p_{n1}^*$  and cases from Scenario II are ruled out; if it is negative  $[c_0 \leq c \text{ or } 1/3 \leq c]$ , it is reached at  $p_{n1}^* \leq c+s$  and cases from Scenario I are ruled out. For cases under Scenario I, we check whether the optimal  $p_{n1}^*$  lies under  $p_{n1}^* < \bar{p}_h$ , i.e. Case 7 or Case 8 which is defined by  $\bar{p}_h \leq p_{n1}^*$ . The derivative of the two-period profit under Case 7 evaluated at  $\bar{p}_d$  is given by  $\delta c(1+\alpha)(2-\delta)-c_r(2+\alpha)-\alpha\delta(1-s)(1-\delta)+\delta^2+\alpha\delta s$ . If this is negative  $[c < \frac{c_r(2+\alpha)+\alpha\delta(1-s)(1-\delta)-\delta^2-\alpha\delta s}{\delta(1+\alpha)(2-\delta)} \doteq c_f]$ , then the optimum lies in Case 7 and is

given by  $\frac{1+\alpha s+c(1+\alpha)}{2+\alpha}$ ; if it is positive,  $[c_f \leq c]$ , the optimum lies under Case 8 and is given by  $\frac{1+c(1+\alpha)+\alpha(s(1-\delta)+\delta^2)}{2+\alpha+\alpha\delta^2}$ .

For cases under Scenario II, we first need to check whether the optimum lies under  $p_{n1}^* < \bar{p}_h$  (Case 17 & Case 18) or  $\bar{p}_h \leq p_{n1}^*$  (Case 19). The derivative of the total profit under the case 19 evaluated at  $\bar{p}_h$  is given by  $c\delta(2-\delta) - 2c_r + \delta^2$ . If this is positive  $[\frac{2c_r-\delta^2}{\delta(2-\delta)} \leq c_u \leq c]$ , the optimum lies under Case 19 and is given by  $1 - \frac{(1-c+\alpha\delta s)}{2+\alpha\delta^2}$  and if it is negative  $[c < c_u]$ , the optimum lies under either Case 17 or Case 18 (based on  $c_q$ ). If  $c < c_u$  and  $c < c_q$ , the optimum lies under Case 17 and is given by  $\frac{1+c}{2}$  and if  $c_q \leq c$ , it lies under Case 18 and is given by  $\frac{1+c}{2}$ .

The two-period optimal decisions under  $c < c_0$  or  $c < 1/3$  are summarized in Proposition 3 and those under  $c_0 \leq c$  or  $1/3 \leq c$  are summarized below:

If the OEM offers a trade-in rebate program for new products and faces competition from a third-party remanufacturer, then the OEM's optimal strategy is dependent on its per-unit production cost  $c$  relative to other parameters as follows:

Condition 1 : If  $c \leq c_3$ , then the optimal prices are given in the table below. In this case, the OEM prices its new product low enough such that the third party does not enter the market ( $q_r^{DR*} = 0$ ).

Condition 2 : If  $c_3 < c < c_4$ , then the optimal prices are given in the table below. In this case, the OEM chooses its list price in a way that some customers in the  $1 - \alpha$  segment buy remanufactured products offered by the third party, whereas others buy new products ( $q_r^{DR*} > 0$ ,  $q_{n2,1-\alpha}^{DR*} > 0$ ).

Condition 3 : If  $c_4 \leq c$ , then the optimal prices are given in the table below. In this case, the OEM chooses its list price in a way that customers in the  $1 - \alpha$  segment only buy remanufactured products ( $q_r^{DR*} > 0$ ,  $q_{n2,1-\alpha}^{DR*} = 0$ ).

### Extended Numerical Analysis

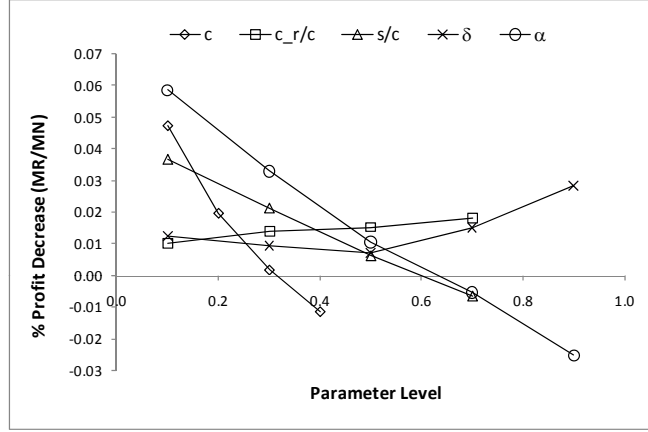
We now perform an extensive numerical study to show that the results from the numerical study in §4.5 (which was over a limited and realistic range of values for the parameters) hold for an extensive range of model parameters. For the parameters  $\alpha$  and  $\delta$  we choose a full-factorial experimental design and vary each of them over their theoretical range  $[0,1]$



with values at 0.1, 0.3, 0.5, 0.7 and 0.9. From the model formulation, we need the following conditions to hold;  $c + s < 1$ ,  $c_r < c$  and  $s < c$ . For the parameters  $c$ ,  $c_r/c$  and  $s/c$  we choose a full-factorial experimental design and vary each of them over their feasible range;  $c$  takes values at 0.1, 0.2, 0.3 & 0.4 and  $c_r/c$  &  $s/c$  take values at 0.1, 0.3, 0.5 and 0.7. Thus, there are a total of  $5^2 \cdot 4^3 = 1,600$  experimental cells. For each experimental cell, we compute the prices, quantities and profits for the OEM for each of the three scenarios studied: the OEM has a monopoly with only the new product ( $MN$ ), the OEM has a monopoly but offers new and remanufactured products ( $MR$ ), the OEM is in a duopoly where the entrant offers a remanufactured product ( $DR$ ). We compare the OEM's profit for cases MR and DR, relative to  $MN$ . For the  $MN$  case, the OEM's profit ranges between 0.18 and 0.49, with a median value of 0.32; for the MR case, the OEM's profit ranges between 0.12 and 0.52, with a median value of 0.31; finally, for the DR case, the OEM's profit ranges between 0.09 and 0.49, with a median value of 0.25. We offer a more detailed comparison between these cases below.

*Case MR: OEM Offers Remanufactured Units* When the OEM offers a remanufactured product, her profit increases (relative to the case  $MN$ ) in only 616 out of 1,600 cells, or 38.5% of the total, with an average profit increase ( $100\% \frac{\pi^{MR*} - \pi^{MN*}}{\pi^{MN*}}$ ) in these cells of 13.51%. Profits decrease in 984 cells (61.5% of the cells), with an average profit decrease of 12.1%. Overall, her average profit across all cells *decreases* by 2.2%, with a maximum decrease of 44.8% and a maximum increase of 82.5%. Thus, the OEM may be worse off by offering a remanufactured product. To analyze which model parameters most contribute to this profit decrease, we averaged, for each factor level, the profit decrease across all corresponding cells. We then plotted the results, which are shown in Figure 10.

Figure 10 clearly shows that the parameters that most influence profit decrease are  $\alpha$ ,  $c$  and  $s/c$ . To provide a clearer picture, we performed individual regressions, one for each experimental factor. For each regression, the dependent variable is the percent profit decrease, the independent variable is the corresponding experimental factor, and there are 1,600 observations. The magnitude of  $R^2$  for each regression provides a metric for the impact of the factor on profit decrease (Wagner 1995). The results are listed in Table 6.



**Figure 10:** Average Profit Decrease when OEM Offers Remanufactured Product

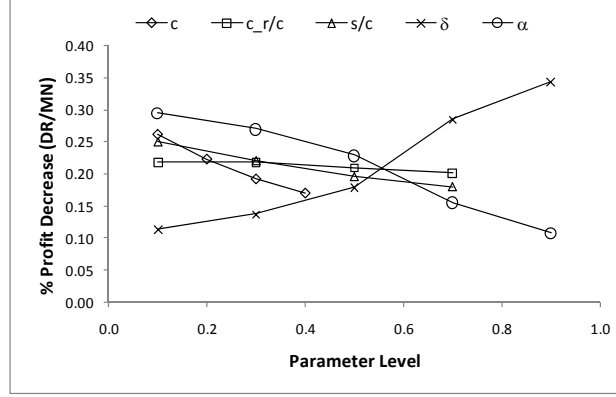
**Table 6:** Individual Regression Results for Profit Deterioration - Case MR

Parameter	Coefficient	$R^2$
$\alpha$	-0.347	0.359
$c$	-0.542	0.137
$s/c$	-0.264	0.130
$c_r/c$	-0.053	0.005
$\delta$	0.0384	0.004

The factors that most impact the decrease in the OEM's profit are, in order:  $\alpha$  (-),  $c$  (-),  $s/c$  (-), and to a less extent  $c_r/c$  and  $\delta$ , with  $R^2$  values of 0.359, 0.130, 0.137, 0.005, and 0.004, respectively. In particular, the factors  $\alpha$  and  $s/c$  account for 35.9% and 13.0%, respectively, of the variation in profit decrease.

*Case DR: Third Party Offers Remanufactured Units* When the entrant offers a remanufactured product, the OEM's profit decreases (relative to the case *MN*) in all 1,600 experimental cells, as one would expect. Overall, the average profit *decrease* is 21.2%, with a maximum decrease of 57.6% and a minimum decrease of 0% (in 10.0% of the cells). Thus, the entry by a third-party remanufacturer significantly worsens the OEM's profits. Again, to analyze which model parameters most contribute to this profit decrease, we have averaged, for each factor level, the profit decrease across all corresponding cells. The results are shown in Figure 11.

Figure 11 clearly shows that the parameters that most influence profit decrease are now



**Figure 11:** Average Profit Decrease when Entrant Offers Remanufactured Product

**Table 7:** Individual Regression Results for Profit Deterioration - Case DR

Parameter	Coefficient	$R^2$
$\delta$	0.304	0.333
$\alpha$	-0.242	0.210
$c$	-0.304	0.052
$s/c$	-0.117	0.030
$c_r/c$	-0.030	0.002

$\delta$ ,  $\alpha$  and  $c$ . Again, we performed individual regressions, one for each experimental factor. For each regression, the dependent variable is the percent profit decrease, the independent variable is the corresponding experimental factor, and there are 1,600 observations. The results are listed in Table 7. Thus, the factors that most impact the profit decrease are, in order:  $\delta$  (-) &  $\alpha$  (-) and to a lesser extent  $c$  (-),  $s/c$  (-) and  $c_r/c$  (-) with  $R^2$  values of 0.333, 0.210, 0.052, 0.030 and 0.002 respectively. In particular, the factors  $\delta$  and  $\alpha$  account for 32.3% and 21.0%, respectively, of the variation in the profit decrease.

We now compare the DR case relative to MR case. That is, how much worse off is the OEM if she does not offer a remanufactured product but the third-party entrant does (DR), compared to the case where the OEM can preempt the entrant by offering her own version of the remanufactured product (MR)? We find the OEM's percent profit decrease ( $100\% \frac{\pi^{MR*} - \pi^{DR*}}{\pi^{MR*}}$ ) from remanufacturing herself versus allowing an entrant to offer remanufactured products is 34.2% on average, with a minimum decrease of 0% (in 10.0% of

cells), a maximum decrease of 55.82%, and a median decrease of 16.9%. Although offering a remanufactured product (typically) cannibalizes sales for the new product (and consequently decreases profit by an average of 2.2%), the OEM is still better off than in the case where a third-party entrant offers the remanufactured product (where the average profit decrease is 34.2%).

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